

Characterization of Nuclear Recoils in High Pressure Xenon Gas:

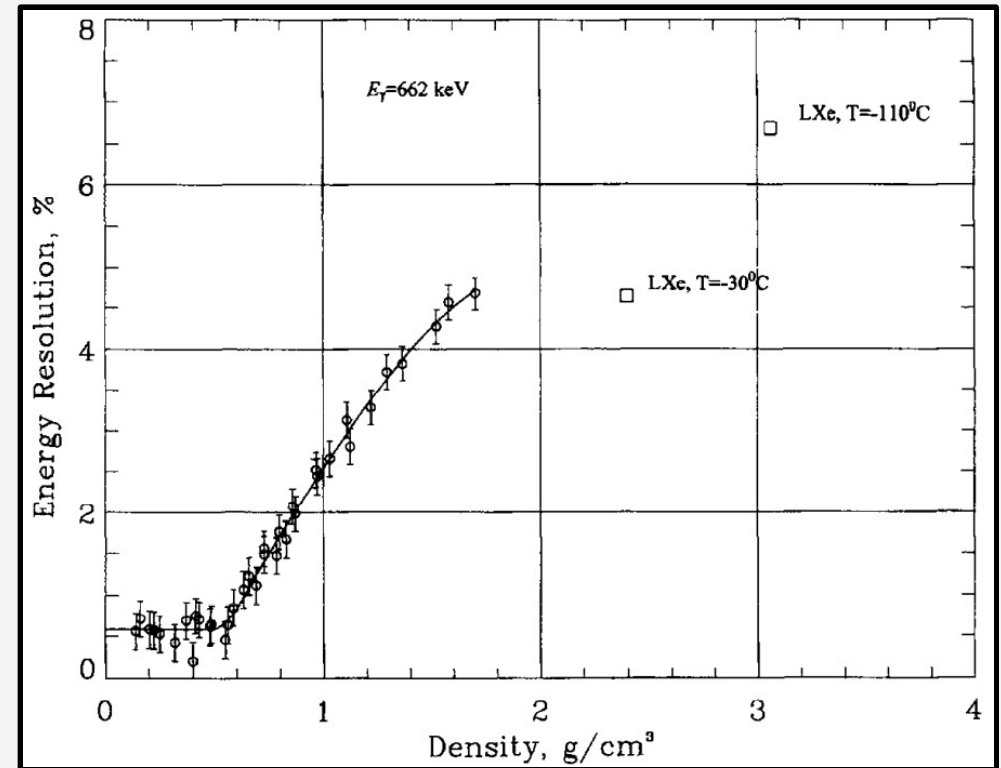
Towards a Simultaneous Search for WIMP Dark Matter
and Neutrinoless Double Beta Decay

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for the NEXT Collaboration
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September 11, 2013

Liquid vs. gaseous xenon: electron recoils

- The gas phase offers:
 - Better intrinsic energy resolution
 $F \sim 0.15$ in gas vs. $F \sim 20$ in liquid, where $(\Delta E/E)^2 = F(W/E)$, and W is the energy to produce an electron-ion pair
 - Attributed to large fluctuations between recombination and scintillation in liquid phase [1]
 - Room temperature operation

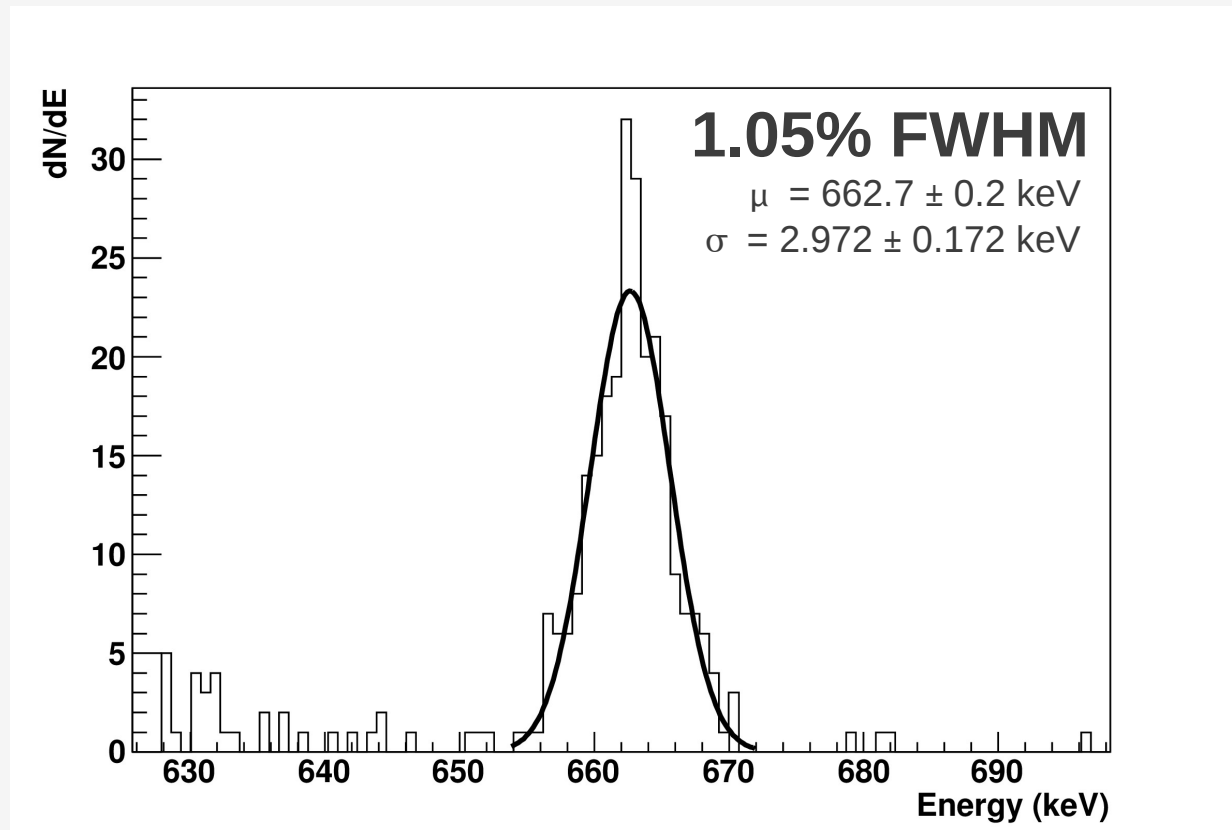


Energy resolution in gaseous xenon with varying density; from [1].

Liquid vs. gaseous xenon: electron recoils

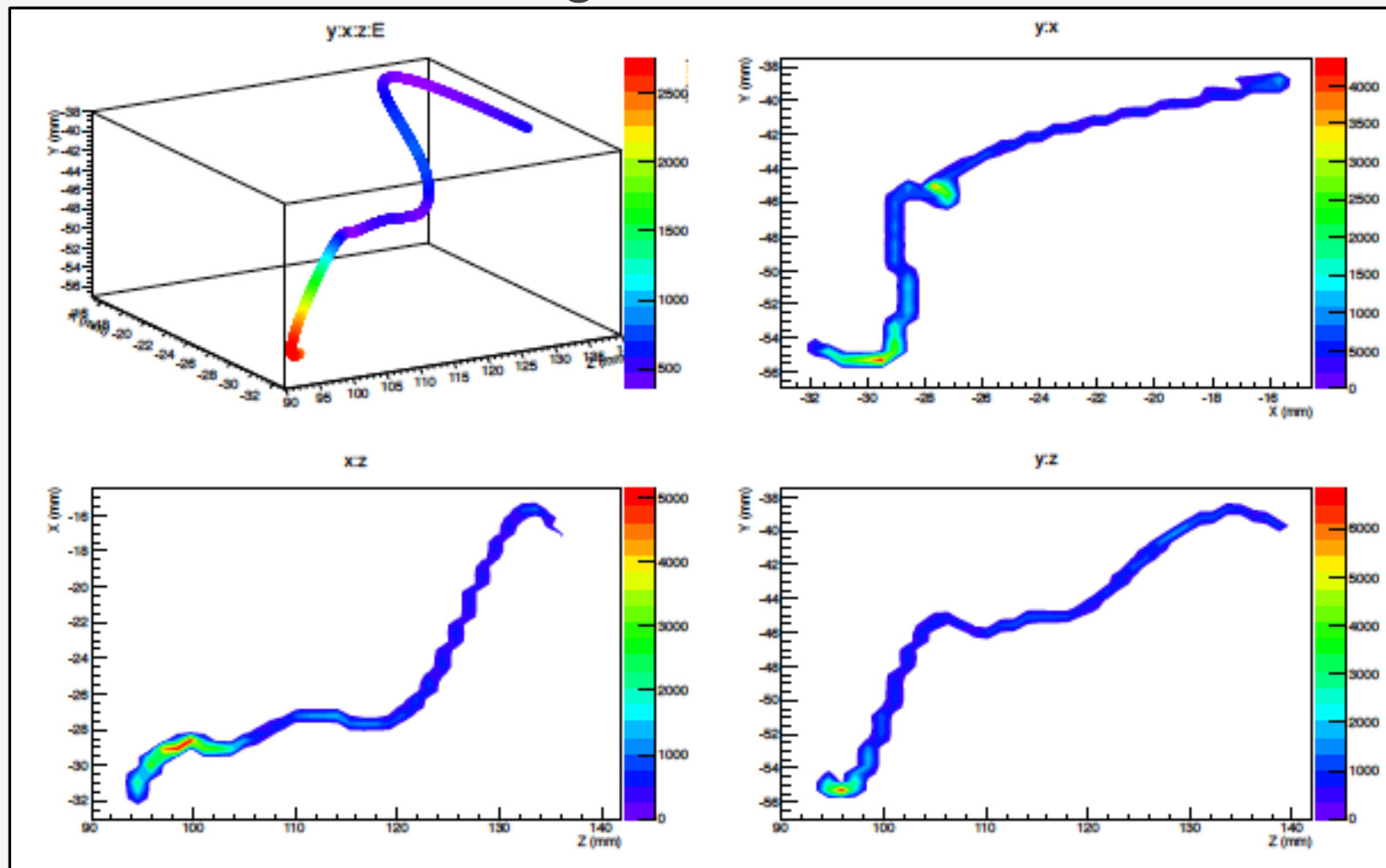
- Electron recoils: energy resolution

- Near-1% FWHM Resolution [1] at 662 keV with tight fiducial cut
- Extrapolate to $Q_{\beta\beta} = 2458.7$ keV [2]:
~0.52% FWHM



Liquid vs. gaseous xenon: electron recoils

- Electron recoils: tracking



^{137}Cs track reconstructed with SiPMs in NEXT-DEMO prototype in Valencia, Spain

Liquid vs. gaseous xenon: electron recoils

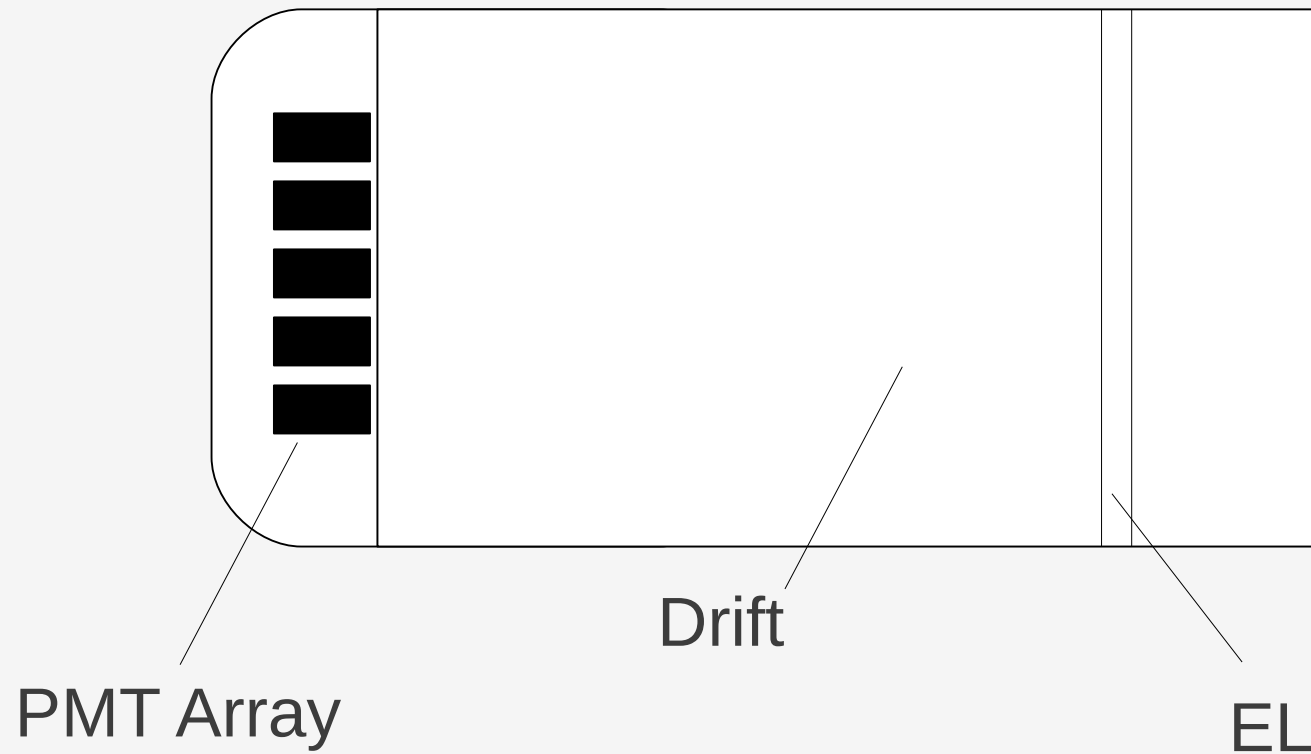
- Perspective:

- gas phase offers good energy resolution using just the ionization signal
- 0.5% energy resolution at $Q_{\beta\beta}$ (EL noiseless gain – maybe also save for after prototype discussion) with topological rejection scheme (tracking)
- opportunity for dark matter searches: low fluctuations gives better resolution in the ratio of ionization to scintillation (S2/S1); better electron/nuclear recoil discrimination

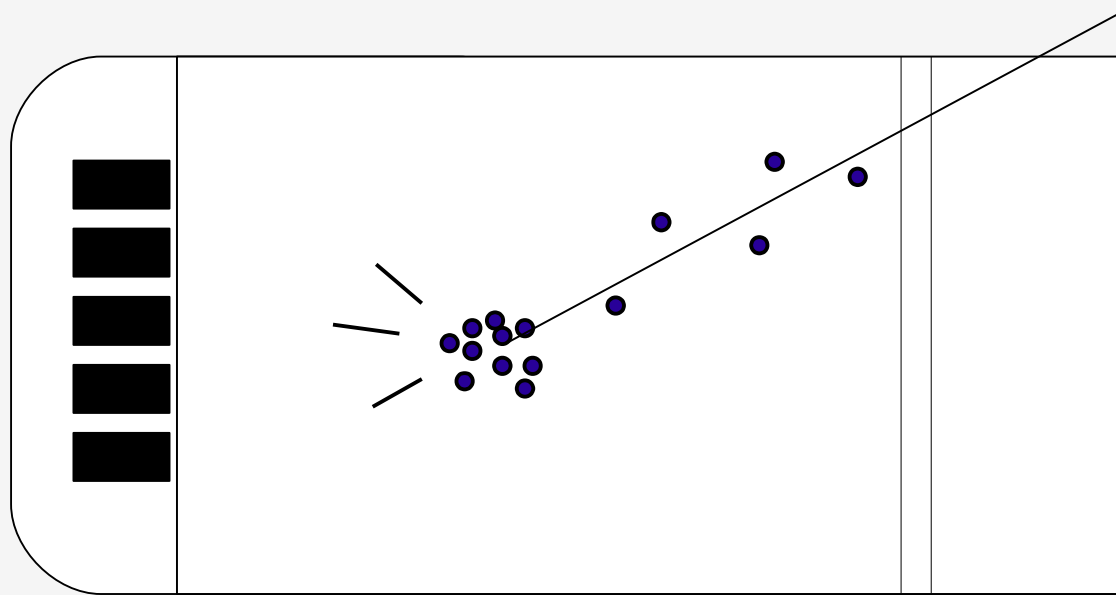
We now understand performance of pure xenon for detection of electron recoils: We wish to investigate response of gas phase xenon to nuclear recoils

Electroluminescence

- An electroluminescent TPC:

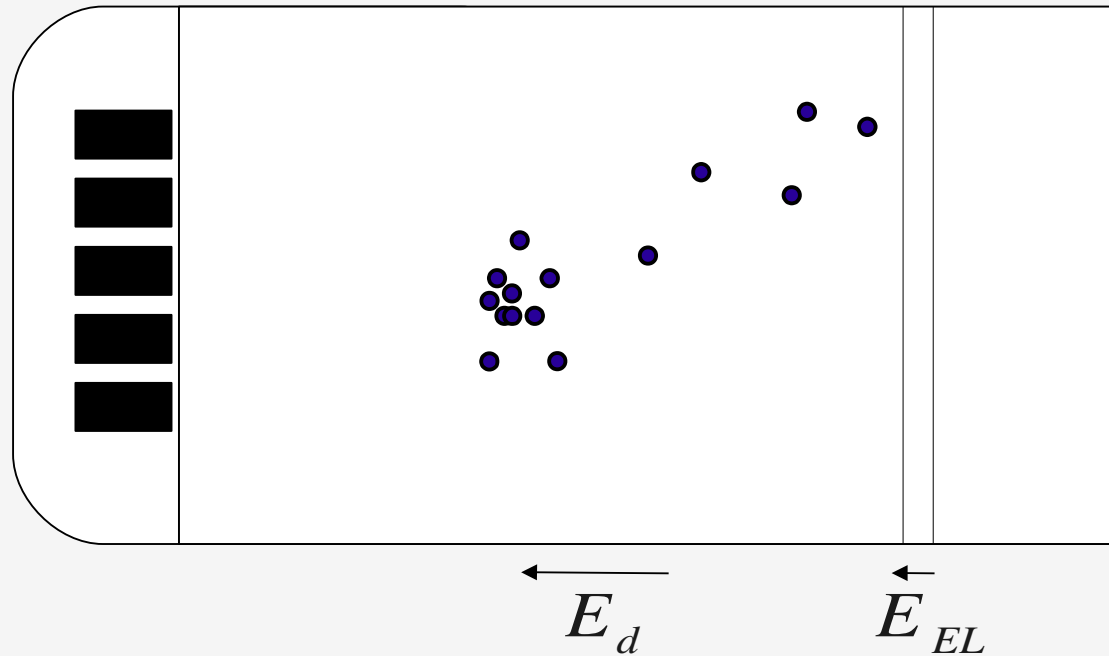


Electroluminescence



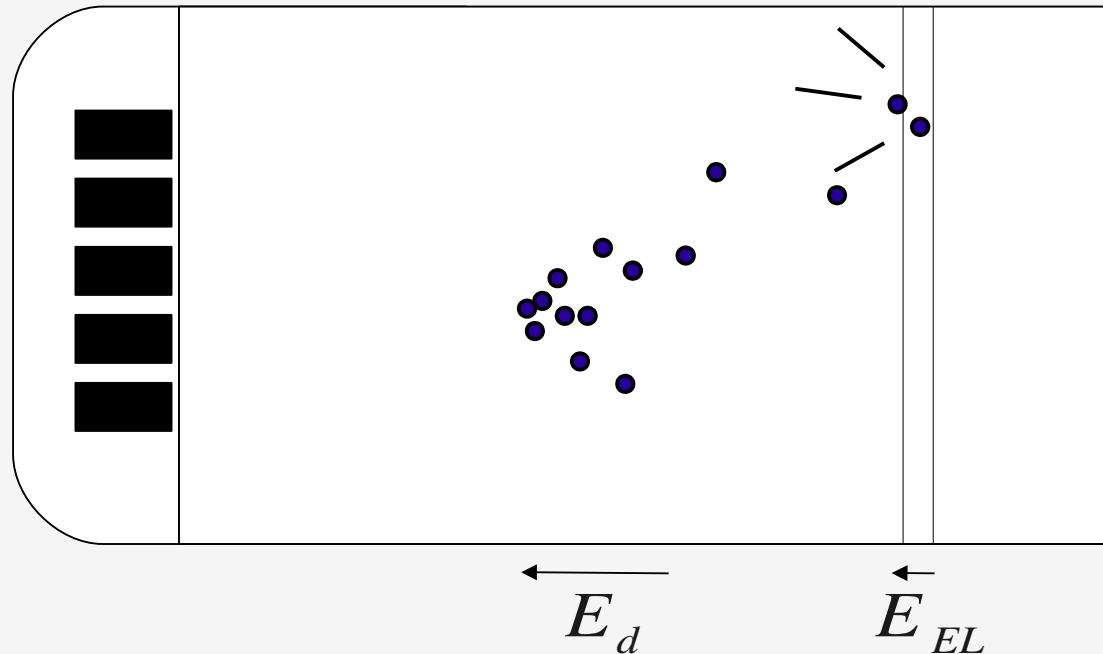
- Incident particle deposits energy, producing ionization (S2) and scintillation (S1)

Electroluminescence



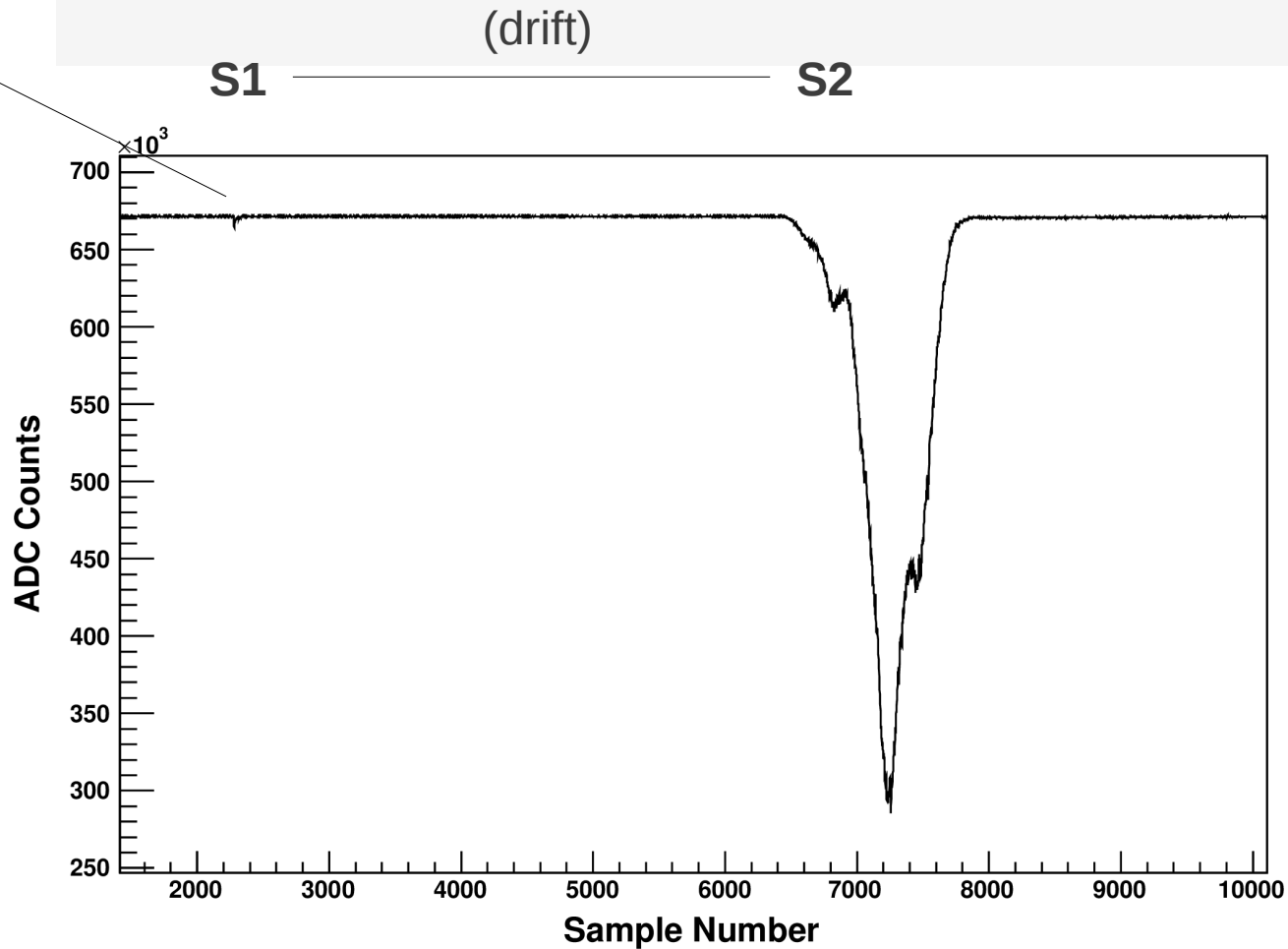
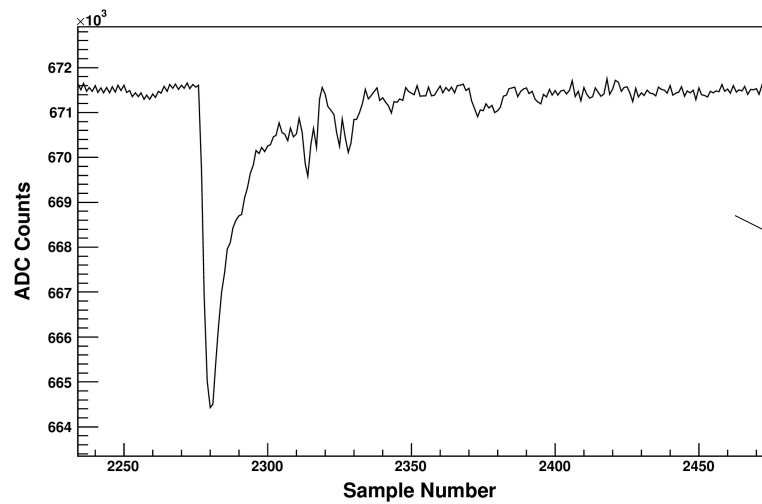
- Electrons drift in an electric field to a narrow region of high field

Electroluminescence



- xenon medium scintillates as the electrons traverse the EL gap; electrons gain enough energy to excite but not ionize xenon atoms

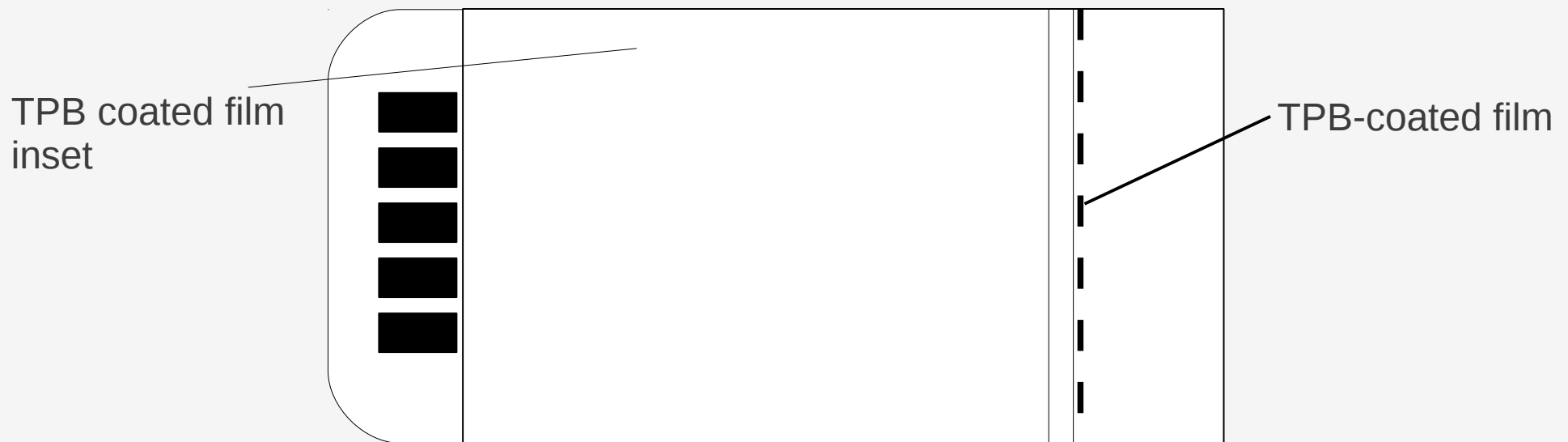
Electroluminescence



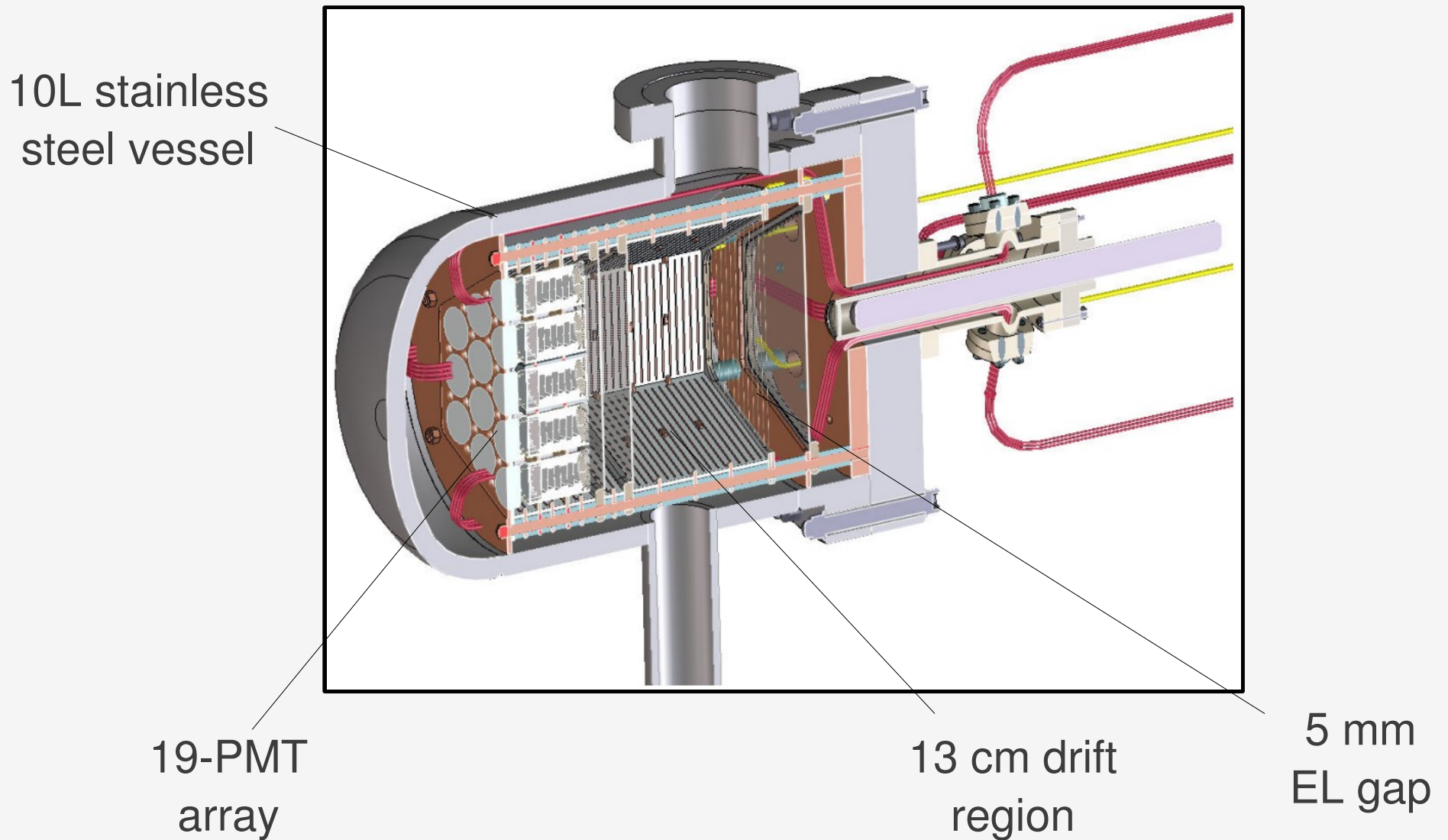
A typical event

Wavelength Shifting:

- TPB (tetraphenyl butadiene)-coated 3M reflective films
 - Placed surrounding drift region and just behind EL region
 - Wavelength shift ~ 170 nm xenon light to ~ 430 nm
 - Factor of ~ 3 better light collection efficiency

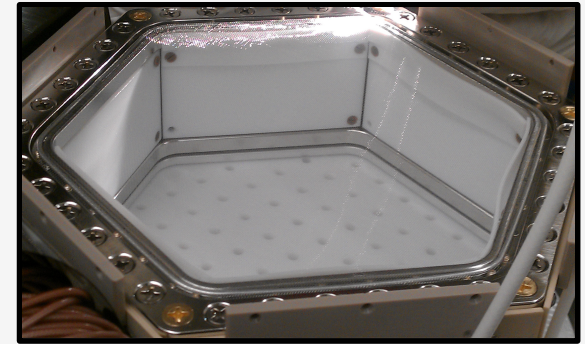
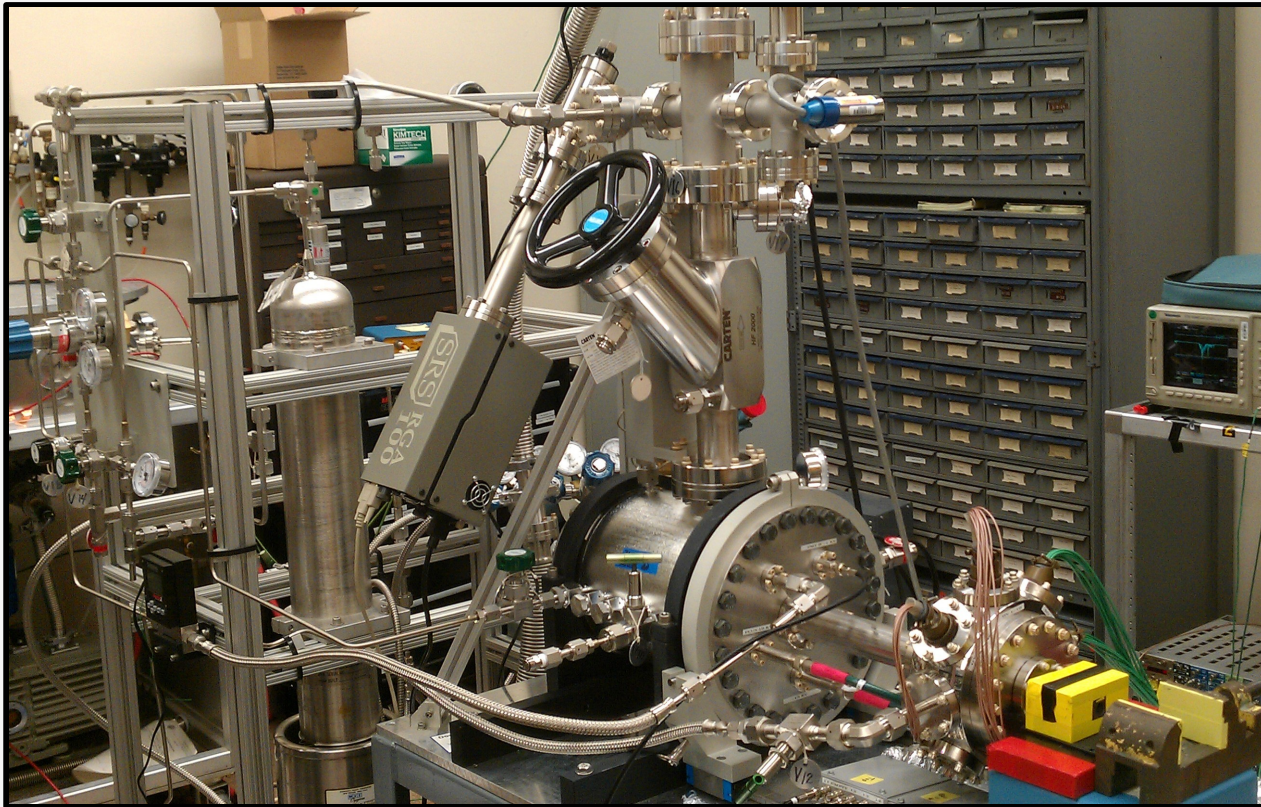


The NEXT-DBDM prototype:

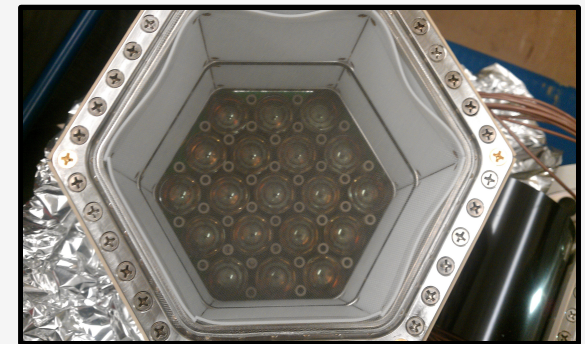


The NEXT-DBDM prototype:

- A prototype for NEXT [1]:
 - NEXT-DBDM: **NEXT Double-Beta Dark Matter**
 - Focus on energy resolution and tracking [1], and now detection of nuclear recoils



Grid

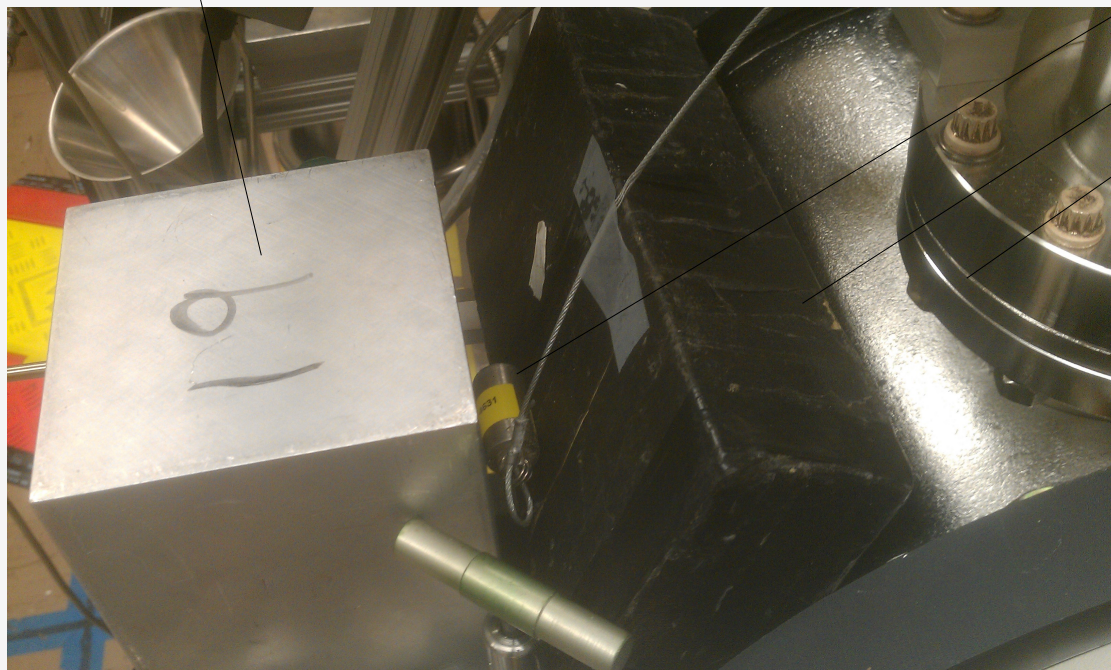


PMT Array

Experimental setup:

- Tag 4.4 MeV γ rays to identify neutron-induced events:
 - ~14 bar xenon gas recirculating through hot getter
 - coincident with approx. 65% of neutron emissions
 - use a NaI scintillating crystal + PMT to detect γ

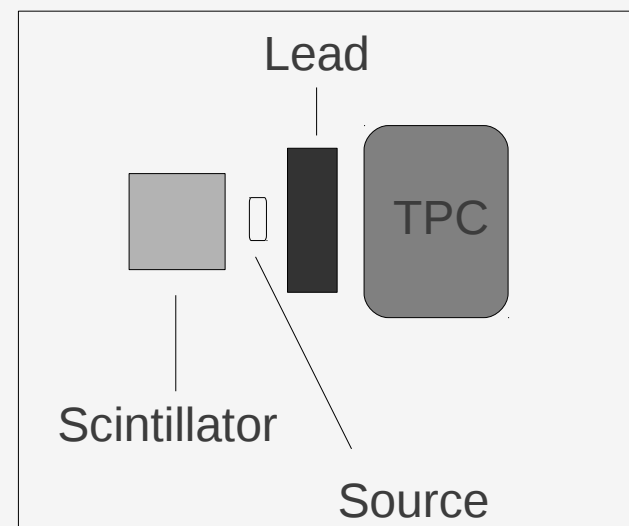
NaI scintillator



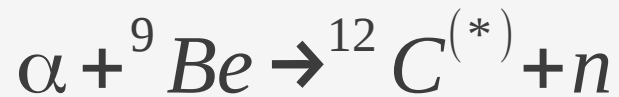
Neutron source $^{238}\text{Pu}/\text{Be}$

Lead block (2" thick)

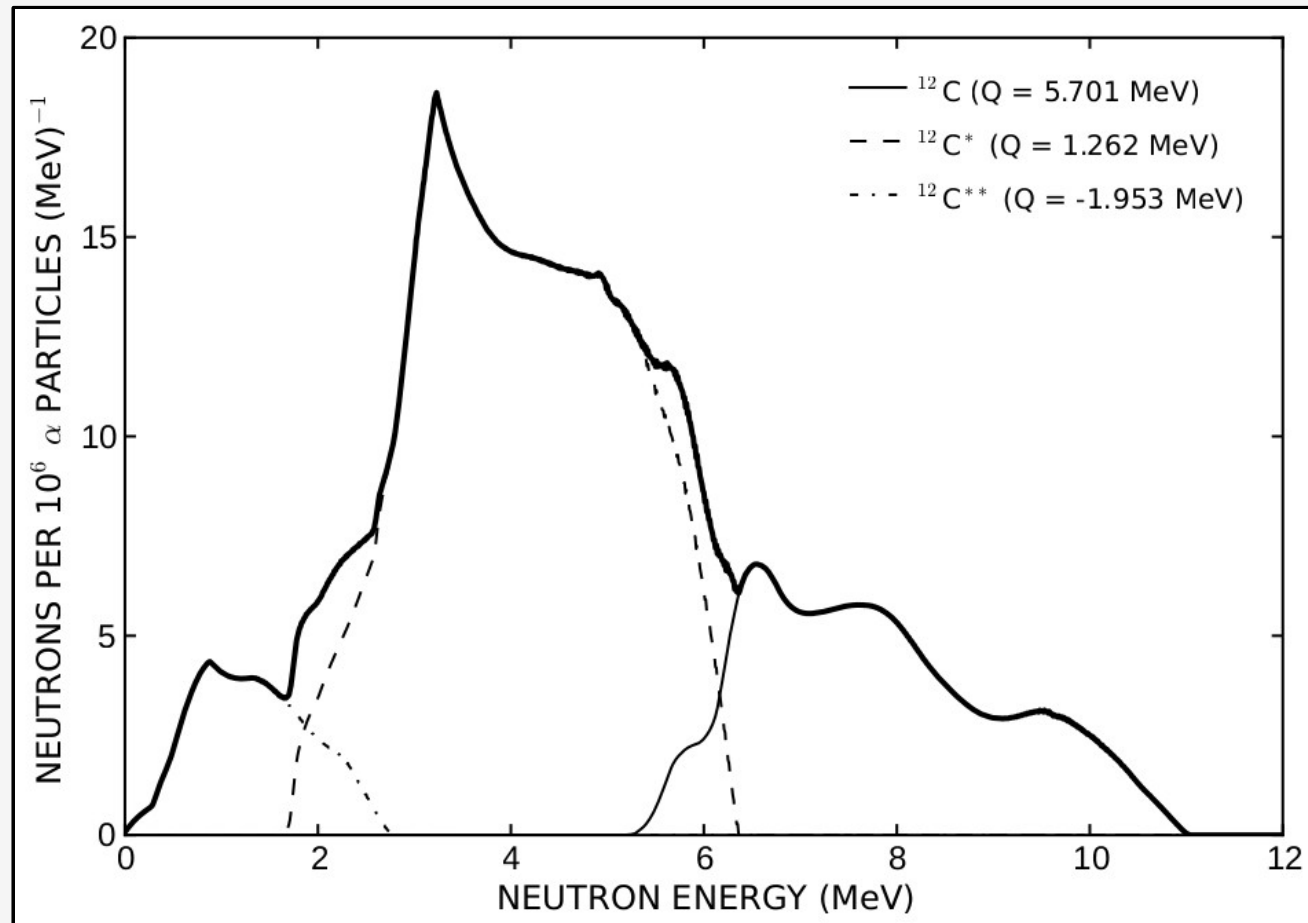
TPC



^{238}Pu -beryllium (α , n) neutron source:



Source spectrum calculated [1-3] for a uniform Pu/Be mix. The $^{12}\text{C}^*$ spectrum is observed, and the decay of the excited C nucleus yields a **4.4 MeV gamma**.



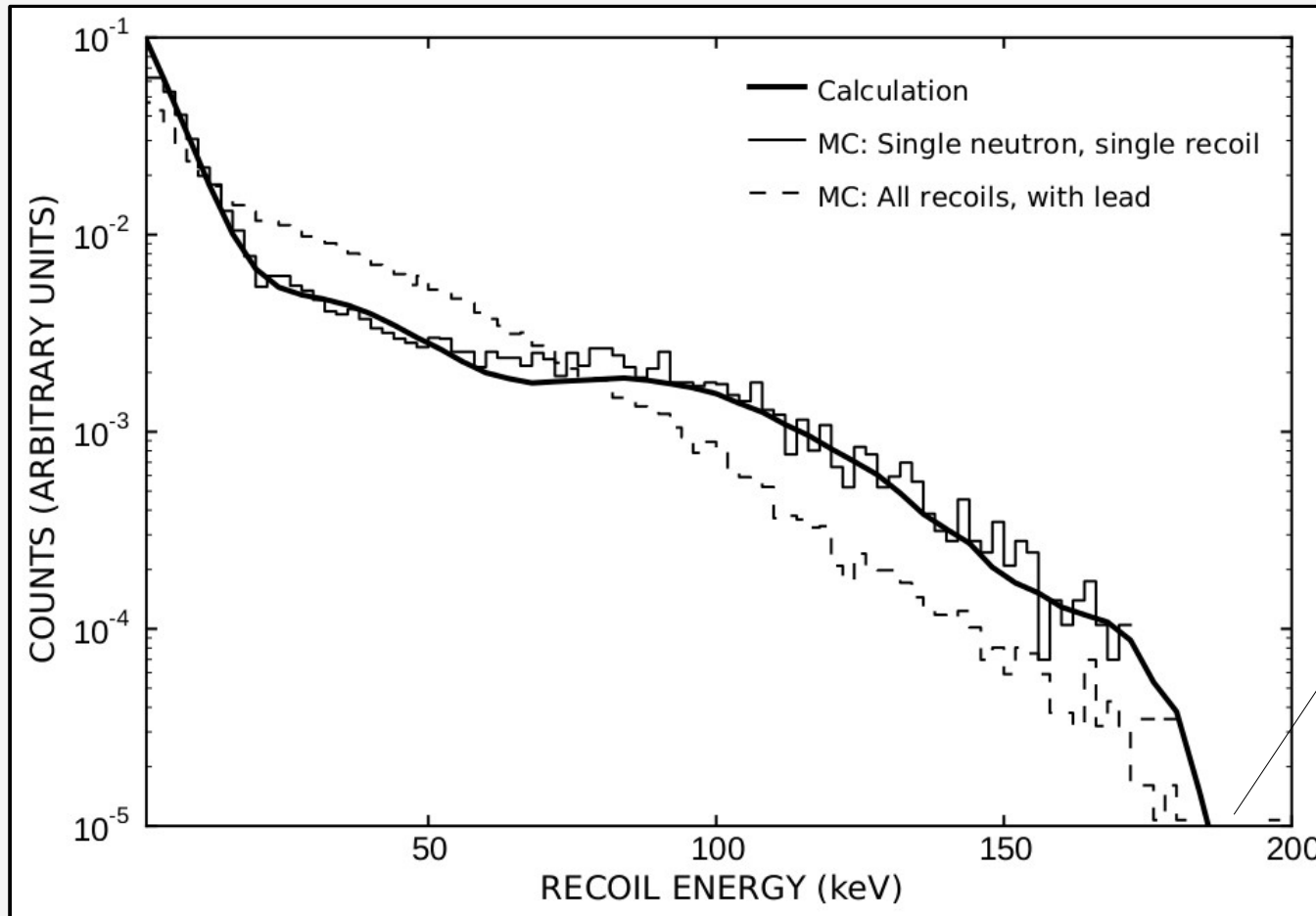
[1] See e.g. K. Geiger and L. V. D. Zwan, Nucl. Instr. Meth. 131, 315 (1975).

[2] T. Murata et al., JENDL (α ,n) Reaction Data File 2005. <http://www.ndc.jaea.go.jp/ftpnd/jendl/jendl-an-2005.html>.

[3] NIST, ASTAR: stopping power and range tables for helium <http://physics.nist.gov/PhysRefData/Star/Text/ASTAR.html>.

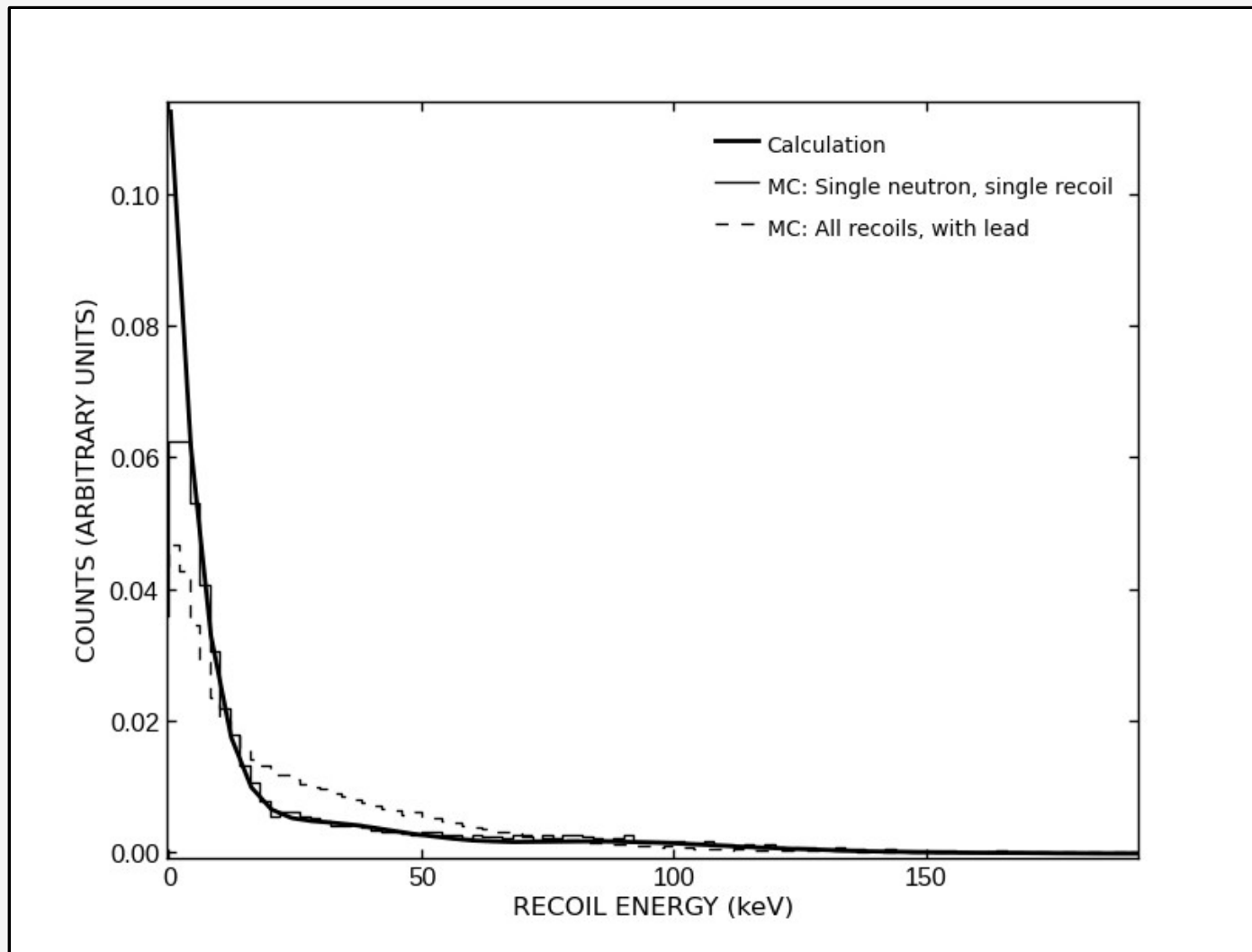
Nuclear recoils in Xe:

- Neutrons create low-energy recoils:
 - maximum recoil for neutron energy E [1] is: $E_{\text{max}} \sim (4/A)E$



$E_{\text{max}} \sim 180 \text{ keV}$ for
 $\sim 6 \text{ MeV}$ neutron

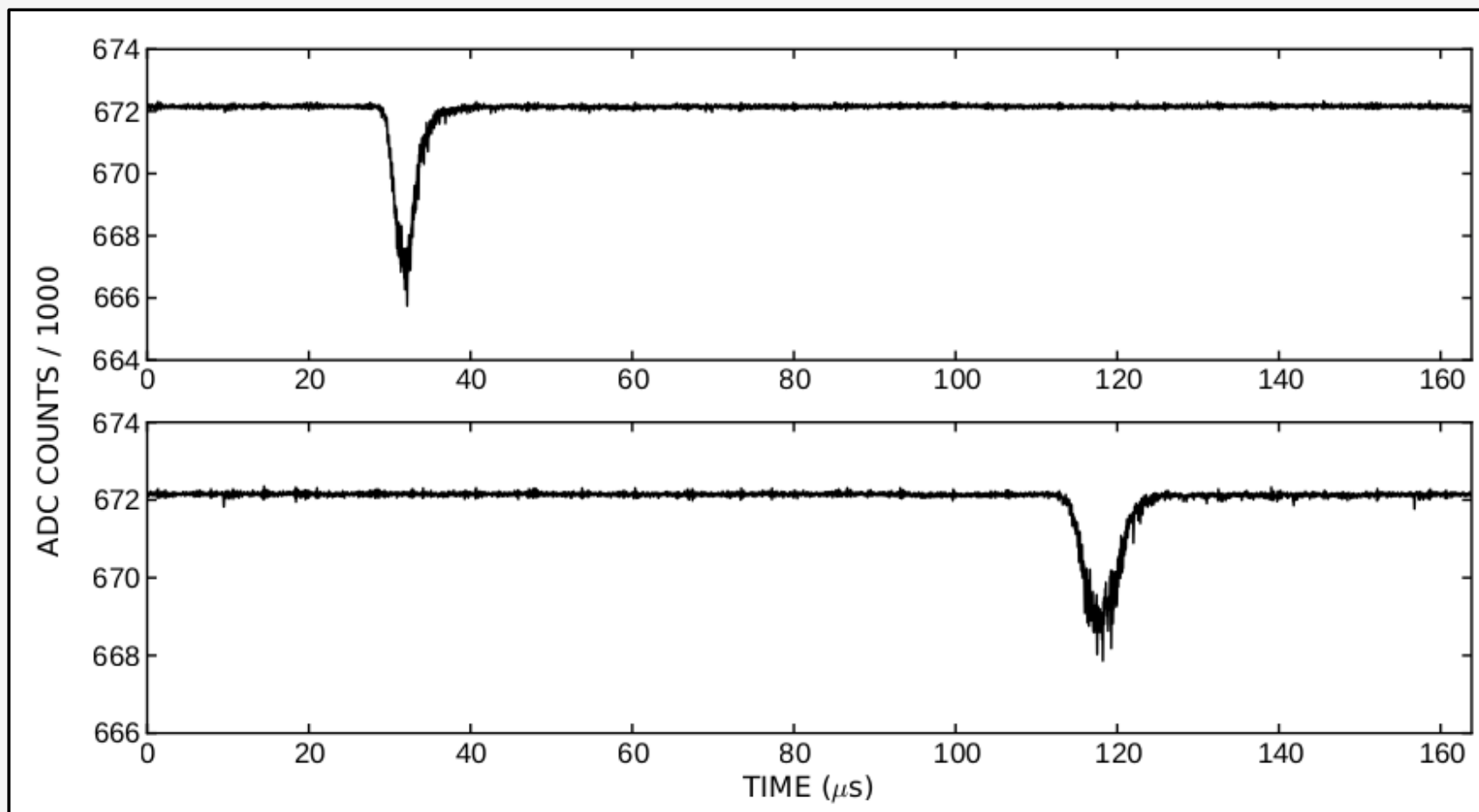
Nuclear recoils in Xe:



Rate is much lower for higher-energy (relatively easier to detect) neutrons

Analysis: waveforms

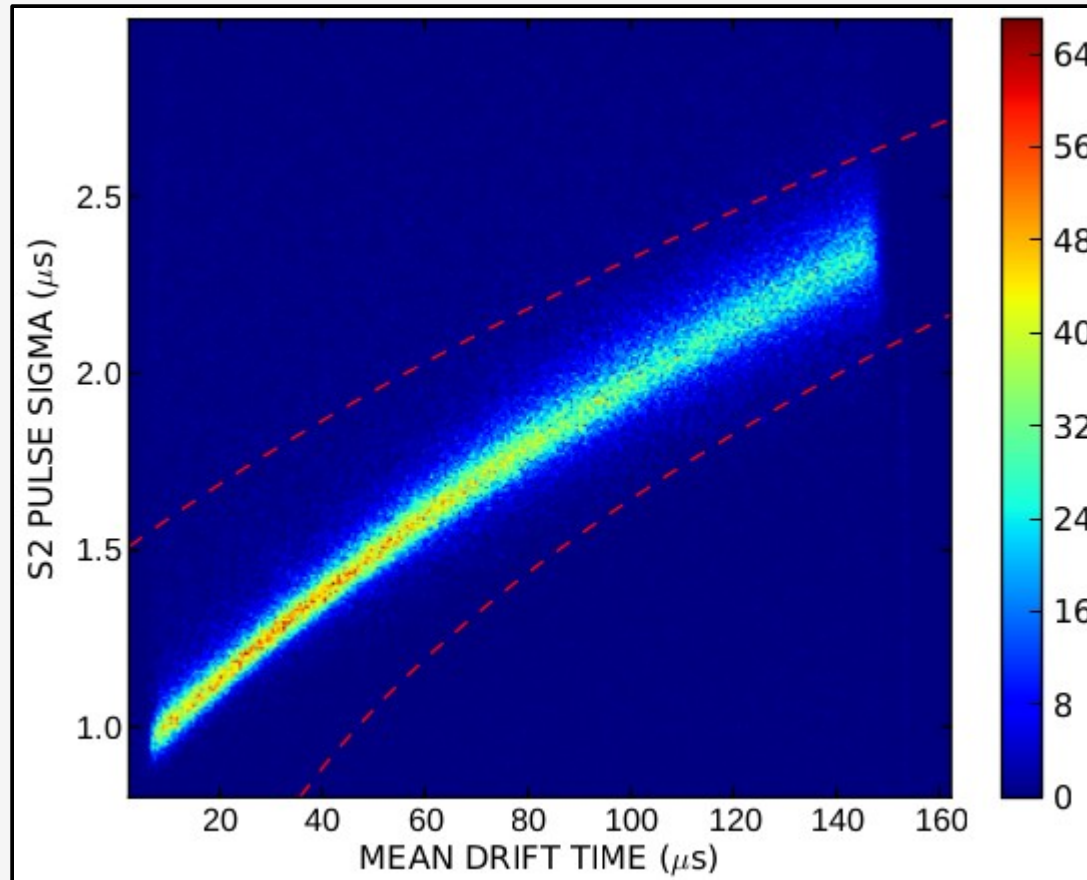
- Candidate neutron events (experiment):



- Single gaussian-like pulses; width is dependent on drift time
- Triggered on S1/NaI (4.4 MeV) coincidence, and S2 NIM-based trigger; waveforms read out using a Struck digitizer

Analysis: diffusion

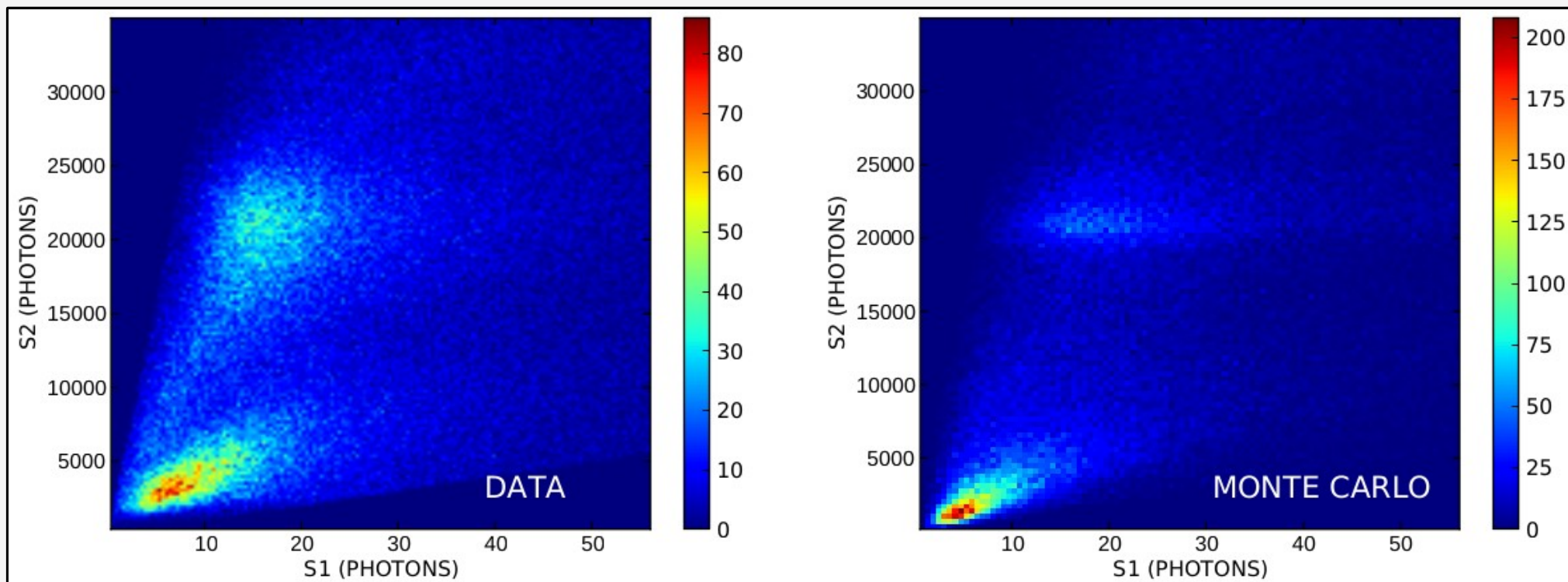
- Diffusion cuts isolate events with correctly chosen S1:



- Single-pulse events in “diffusion band” are those for which S1 was properly identified
- Diffusion consistent with $\sim 0.5 \text{ mm/cm}^{1/2}$

Analysis: S1 vs. S2

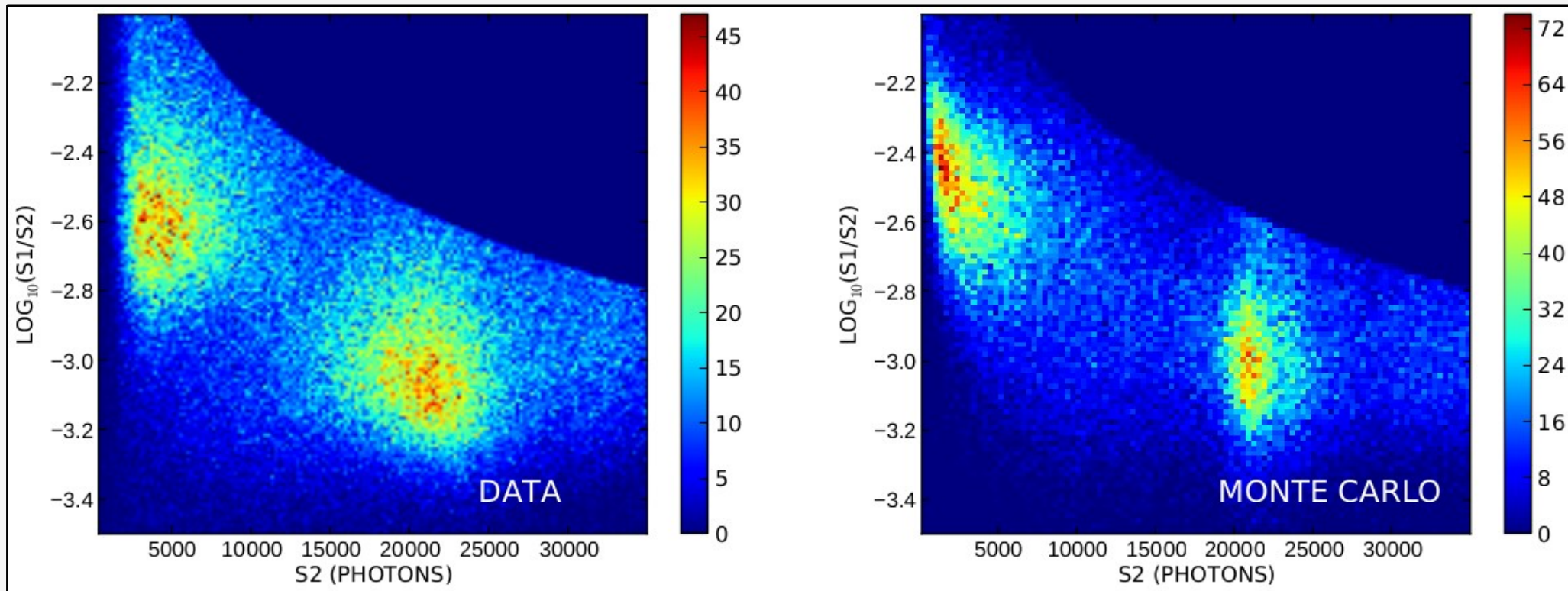
- Nuclear and electron recoils separable at high energies:



- Monte Carlo quenching set to $1/2.14$ for S1, $1/6.15$ for S2; constant in energy (not the case in liquid xenon)
- More low-energy gamma background present in data
- Energy resolution in data unexpectedly poor, perhaps due to TPB

Analysis: S1/S2

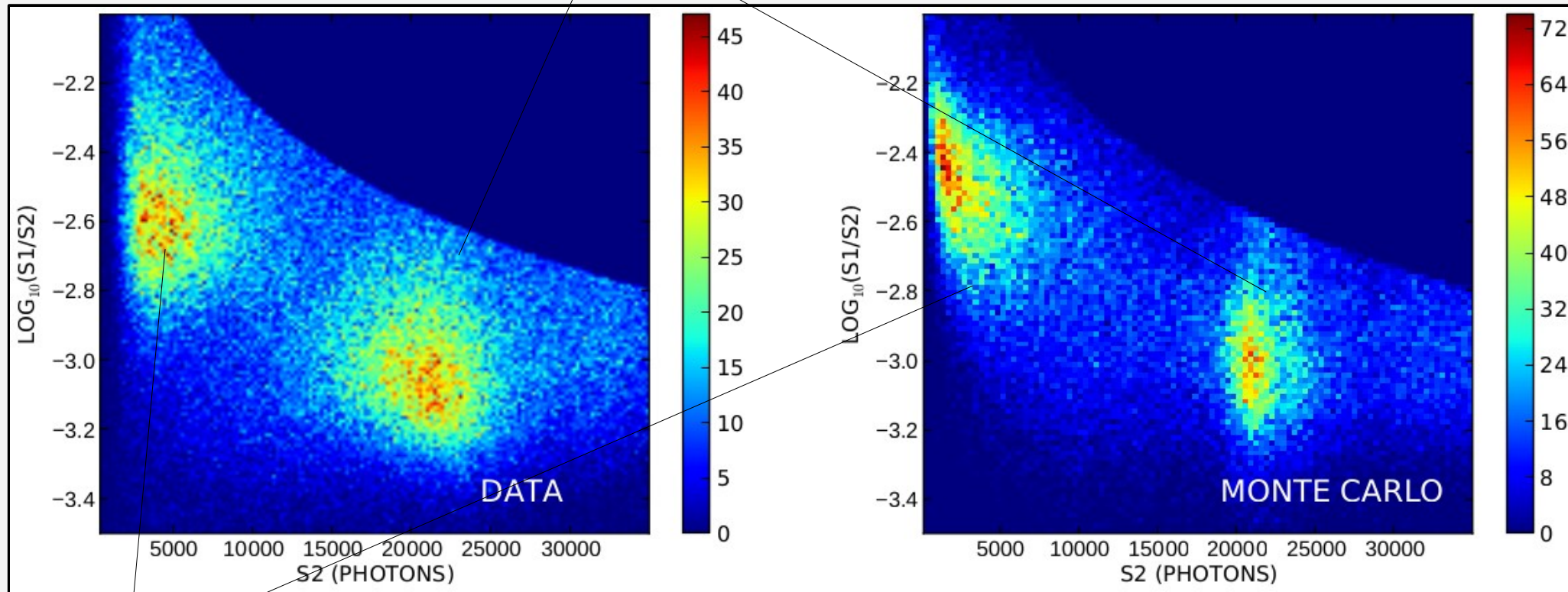
- Clear separation between neutrons and gammas:



Analysis: S1/S2

- Clear separation between neutrons and gammas:

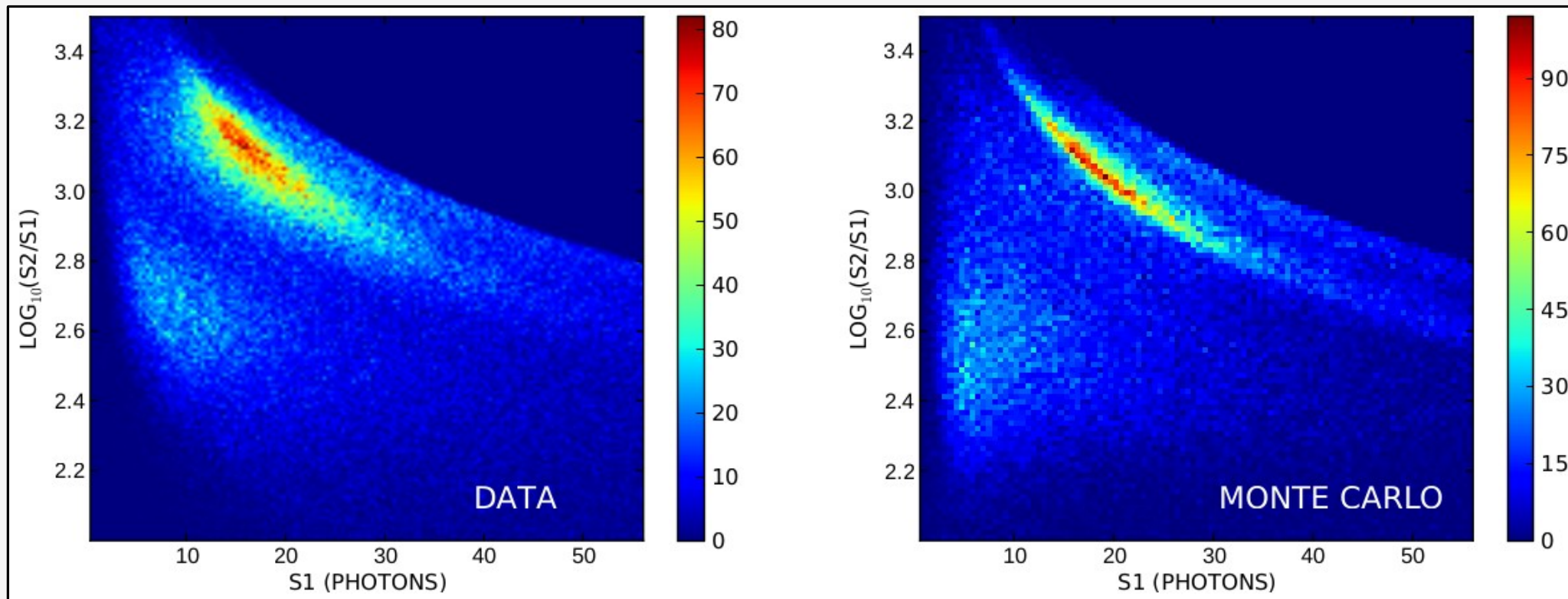
Electron recoils (mostly x-rays)



Nuclear recoils

Analysis: S2/S1

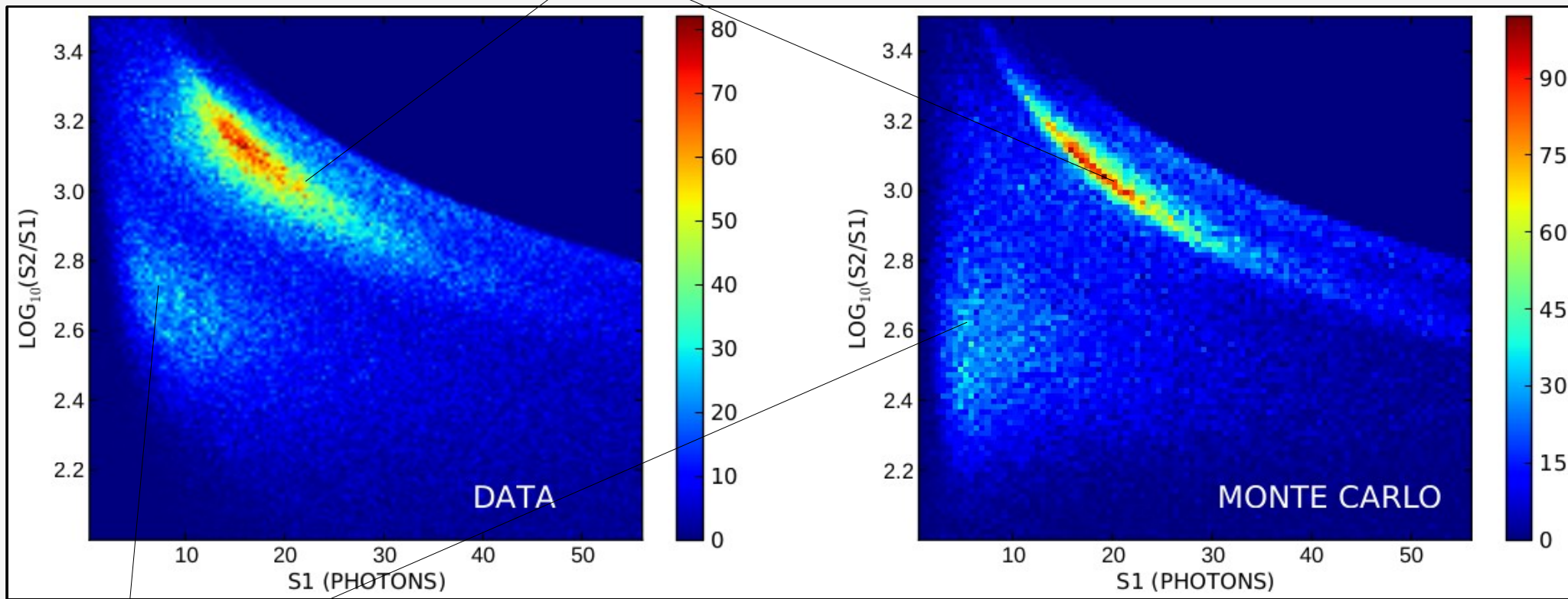
- Clear separation between neutrons and gammas:



Analysis: S2/S1

- Clear separation between neutrons and gammas:

Electron recoils (mostly x-rays)



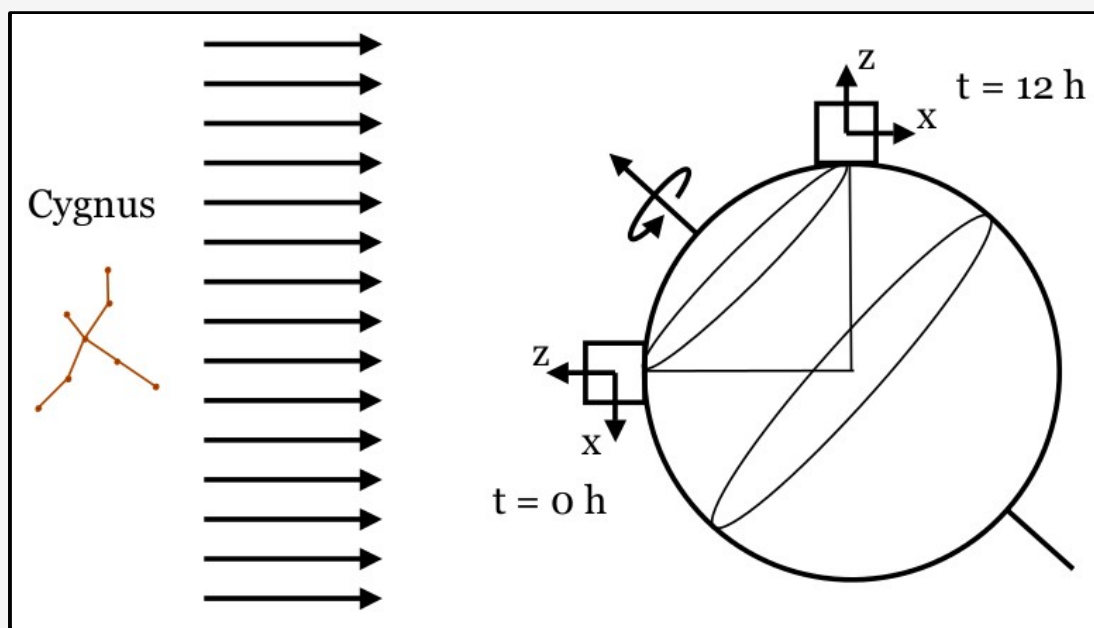
Nuclear recoils

Conclusions - nuclear recoils in xenon gas:

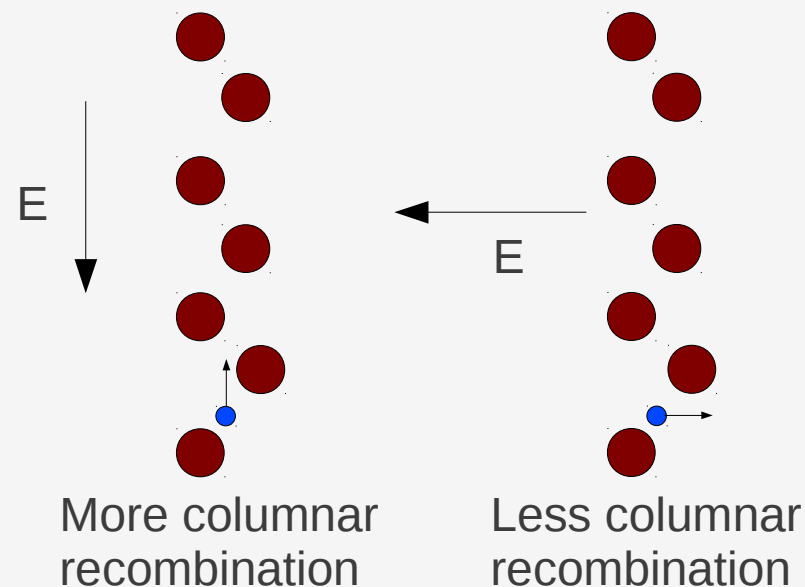
- Gas provides reasonable electron/nuclear recoil discrimination
 - S2/S1 significantly different for two types of events
 - exact yields and their energy dependencies still unknown
- Better understanding of experimental setup and hardware trigger is required:
 - Factor of ~ 15 difference in calculated and expected source rate based on event rate computed from Monte Carlo
 - Apparent reduction in rate at lower drift fields
 - Degradation in energy resolution since the time of the electron recoil studies (possibly due to use of TPB)

Ton scale + directionality:

- Columnar recombination and track orientation:
 - WIMPs in a dark matter “halo” would cause nuclear recoils with a preferred direction [1]
 - Recombination signal in gas may provide the information necessary to determine nuclear recoil direction relative to an external field (idea of Dave Nygren)



From [1]



Simultaneous $0\nu\beta\beta$ and dark matter search:

- Large gaseous xenon detector:
 - Similar detection strategies and requirements for both searches

Combines:

✓ good energy resolution

✓ tracking

(✓) electron/nuclear recoil discrimination

(?) nuclear recoil directionality

See posters by Carlos Oliveira and Dave Nygren

Thank You

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- the Director, Office of Science, Office of Basic Energy Sciences, of the U.S. Department of Energy (Contract No. DE-AC02-05CH11231)
- the National Energy Research Scientific Computing Center (NERSC), supported by the Office of Science of the U.S. Department of Energy, (Contract No. DE-AC02-05CH11231)
- a Department of Energy National Nuclear Security Administration Stewardship Science Graduate Fellowship, (Contract No. DEFC52-08NA28752)

Additional Slides

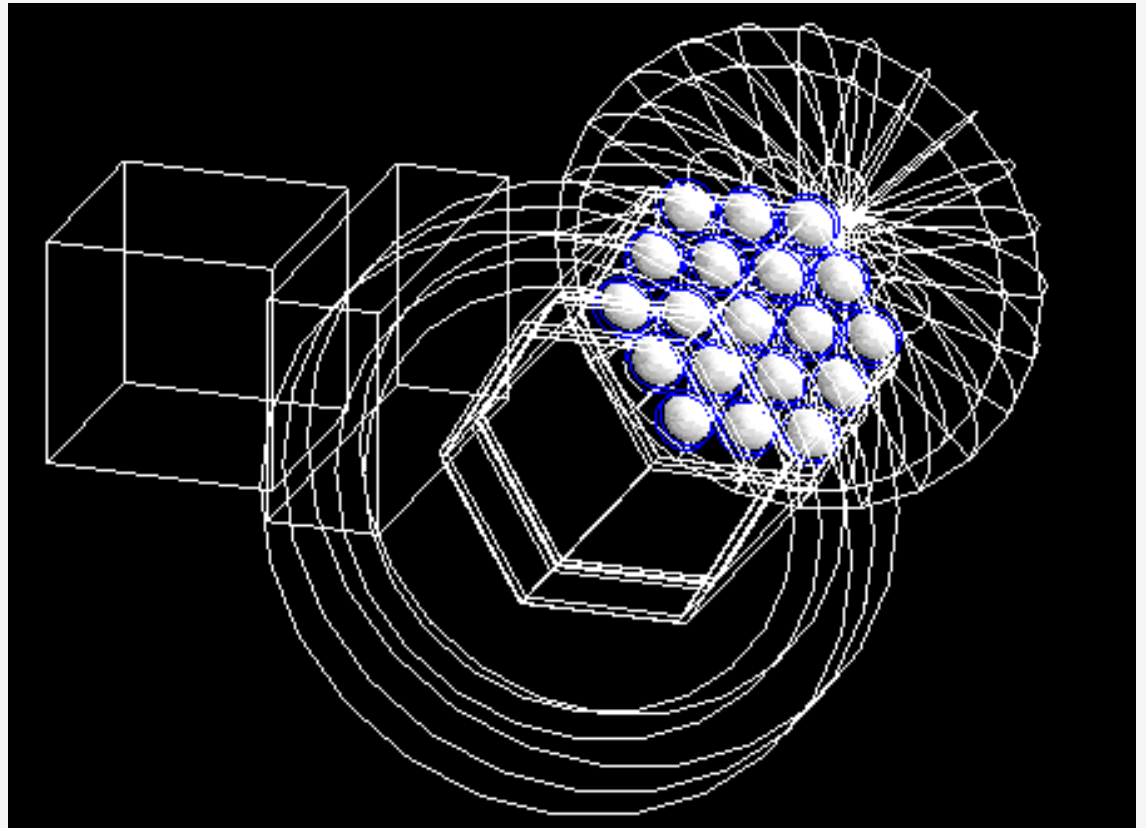
Nuclear recoils: Monte Carlo (GEANT)

- Contains steel vessel, drift and EL regions, PMTs, lead block, and NaI crystal
- $W = 21.9$ eV,
 $W_{sc} = 100$ eV,
EL gain and PMT QE matched to give approx. correct S1 and S2 yields
- Nuclear recoils modeled as “generic ions” in GEANT

$$S1_{NR}/S1_{\gamma} = 1/2.14$$

$$S2_{NR}/S2_{\gamma} = 1/6.15$$

Neutron spectrum input
from calculation



The NEXT experiment:

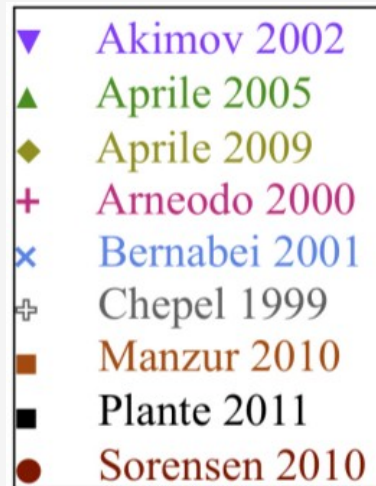
- A $0\nu\beta\beta$ experiment in Canfranc, Spain [1]
 - up to 150 kg of Xe, enriched to isotope ^{136}Xe
 - 1.36 m diameter, 2.28 m long cylindrical main vessel
 - ~7000 SiPM-tracking plane; 60 3-in. PMT energy plane
 - electroluminescent gain
 - expected resolution near 0.5% FWHM at $Q_{\beta\beta}$

Funding secured
from the ERC
this year

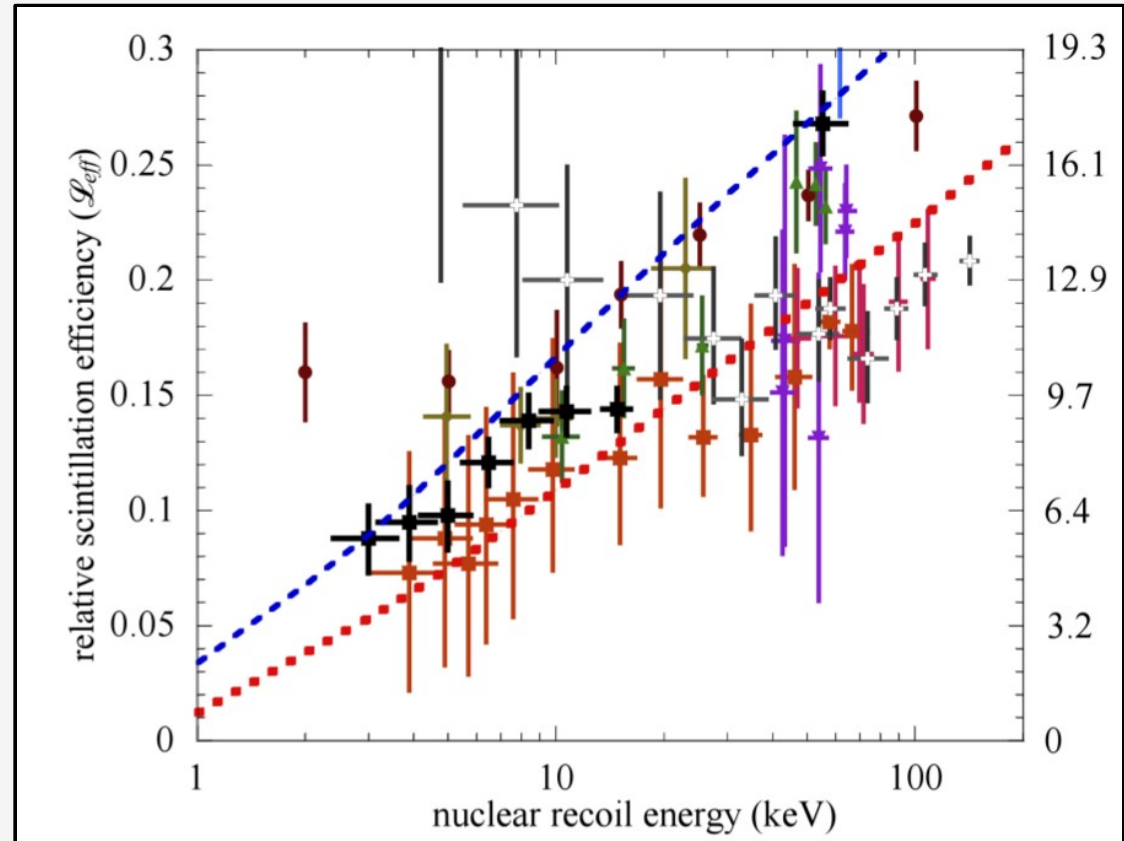
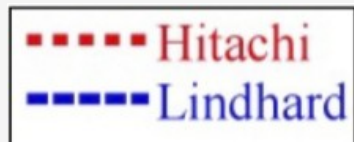


Liquid vs. gaseous xenon: nuclear recoils

- S1 and S2 yields for recoils in gas are unknown:



NEST:



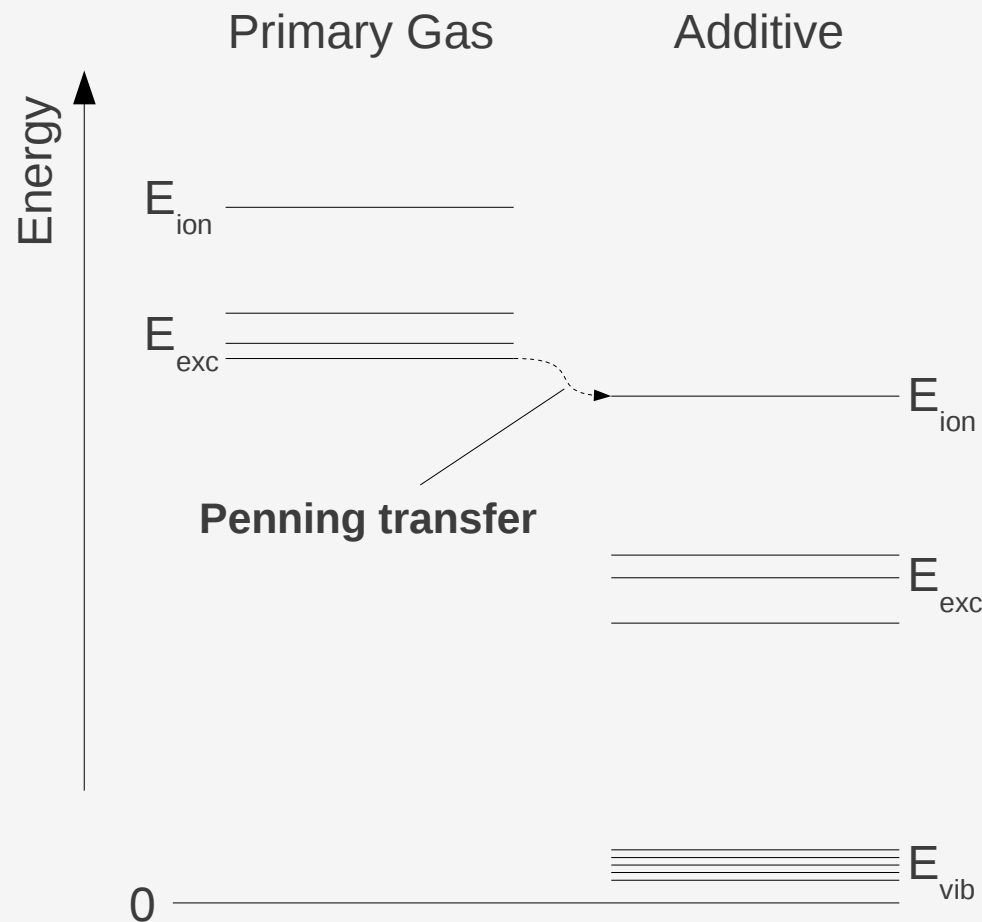
- Same energy dependence and magnitude in gas?

Relative scintillation efficiency in liquid xenon; from NEST [1].

Molecular additives:

- Could provide several advantages:

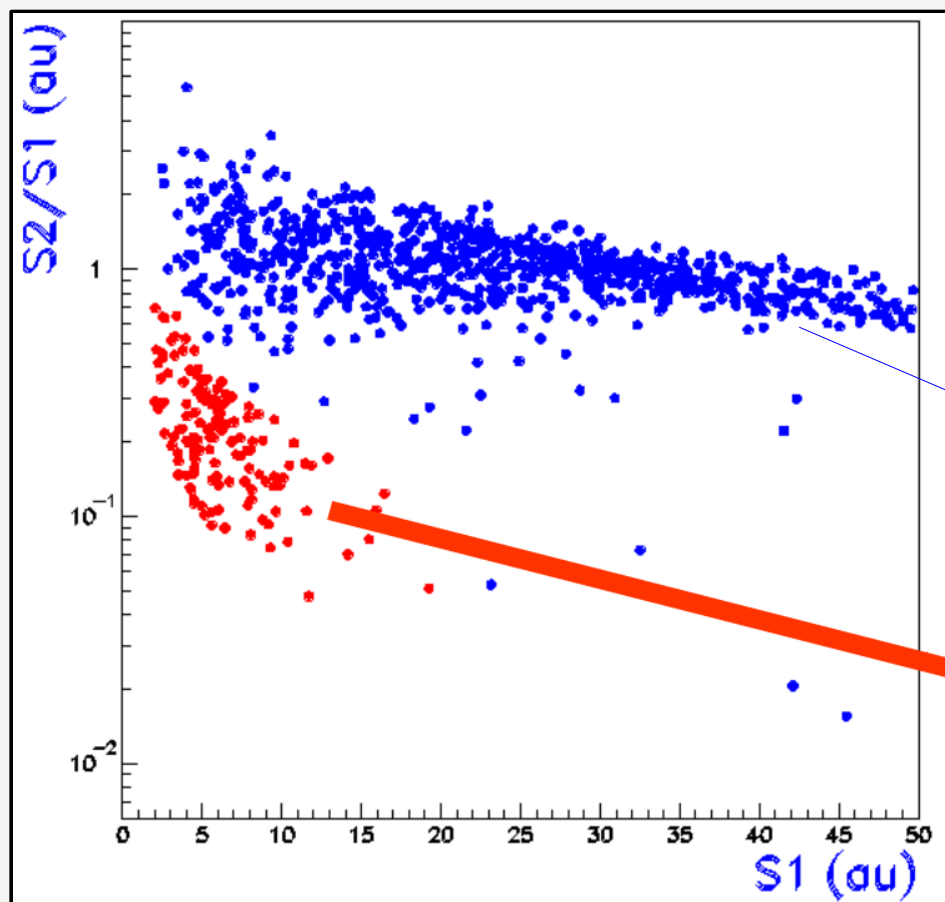
- Penning effect: conversion of excitation into ionization, eliminates primary S1
- cooling of electrons potentially increases columnar recombination; improved directionality signal



See poster by Carlos Oliveira

Liquid vs. gaseous xenon: nuclear recoils

- Measurements taken at TAMU (J. White):



- Small 7-PMT test cell, 20 bar Xe gas
- Electron/nuclear recoil discrimination
- Monoenergetic neutrons

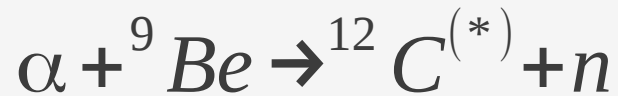
Electron recoils

Nuclear recoils

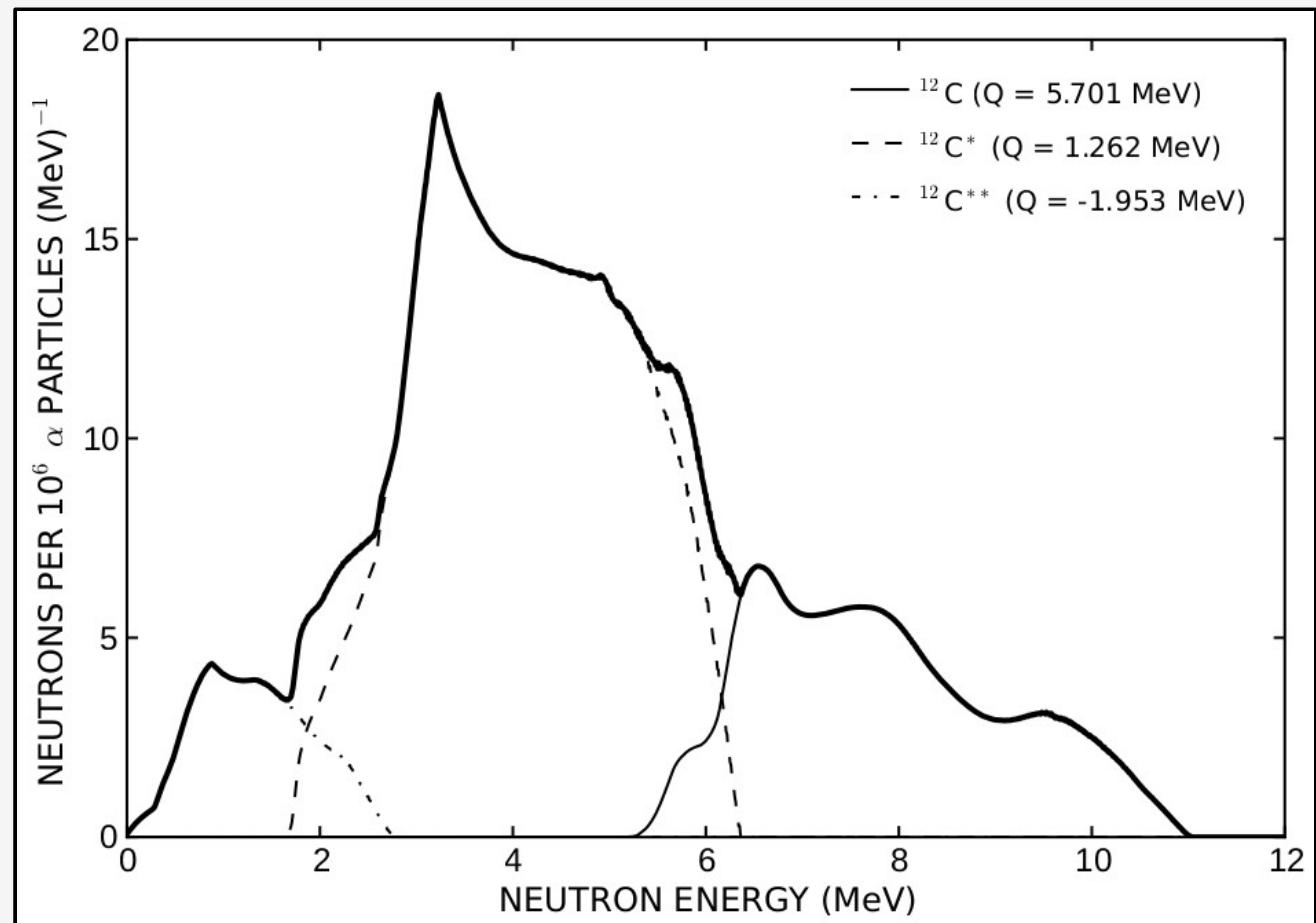
From [1]

- Gas phase requires further study

^{238}Pu -beryllium (α , n) neutron source:



Source spectrum calculated [1] for a uniform Pu/Be mix from JENDL [2] (α , n) cross sections and angular distributions, and dE/dx in ${}^9\text{Be}$ from NIST ASTAR [3]. The ${}^{12}\text{C}^*$ spectrum is observed, and the decay of the excited C nucleus yields a **4.4 MeV gamma**.



$$N(E_n; E_{\alpha,i}) = \int_0^{E_{\alpha,i}} dE_{\alpha} \frac{4\pi [d\sigma(E_{\alpha}; E_n)/d\Omega]}{dE_{\alpha}/(\rho dx) [E_n(0) - E_n(\pi)]}$$

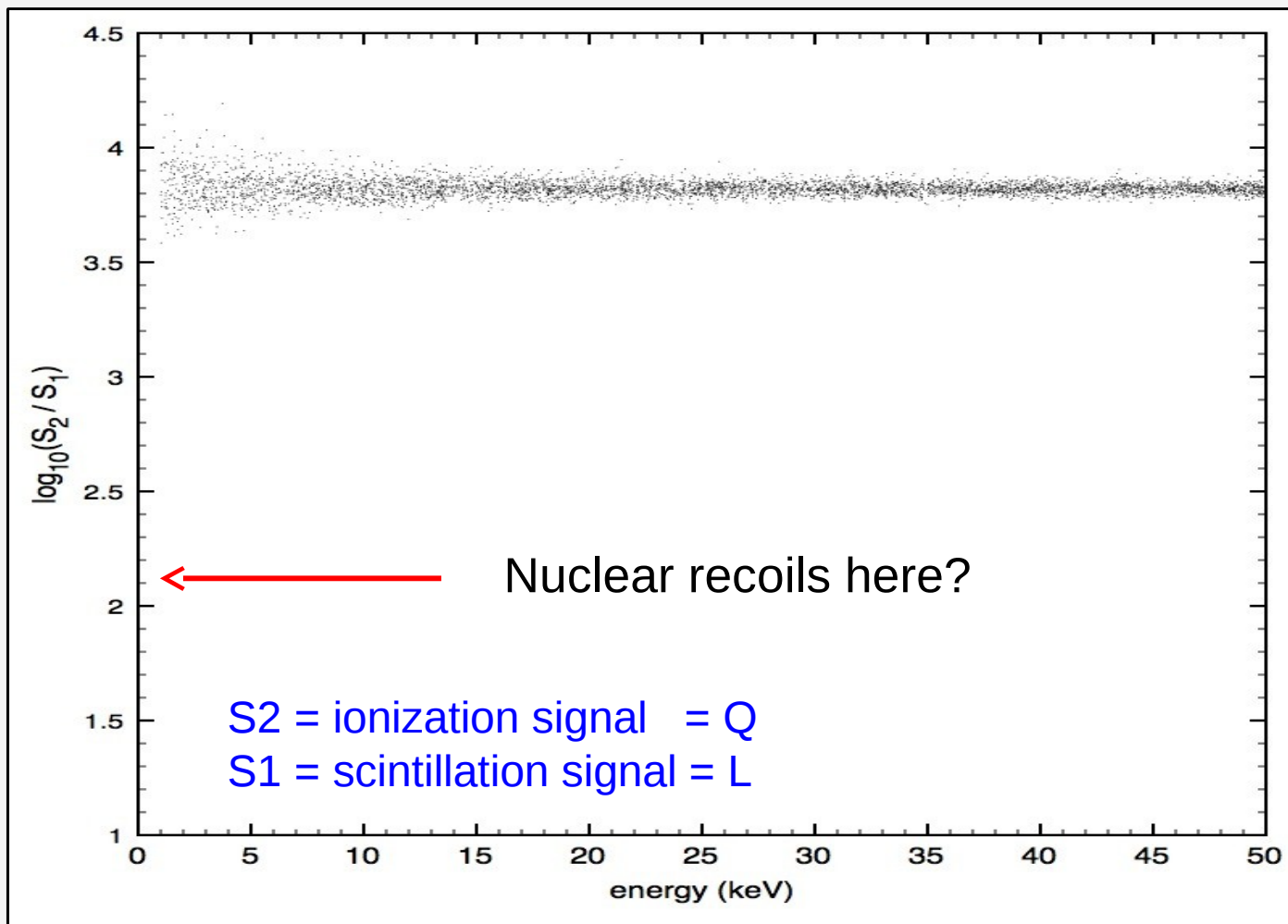
[1] See e.g. K. Geiger and L. V. D. Zwan, Nucl. Instr. Meth. 131, 315 (1975).

[2] T. Murata et al., JENDL (α ,n) Reaction Data File 2005. <http://www.ndc.jaea.go.jp/ftpnd/jendl/jendl-an-2005.html>.

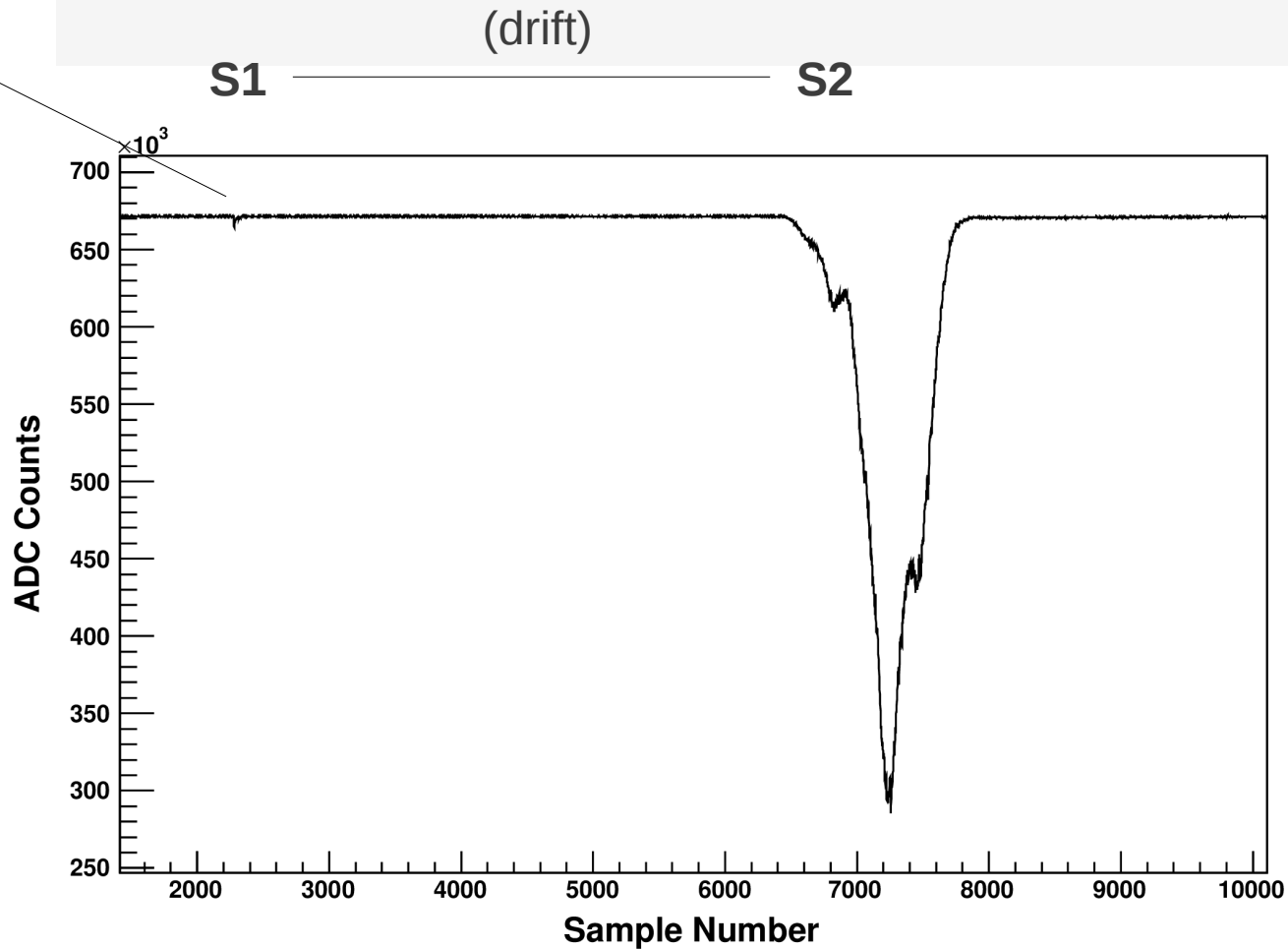
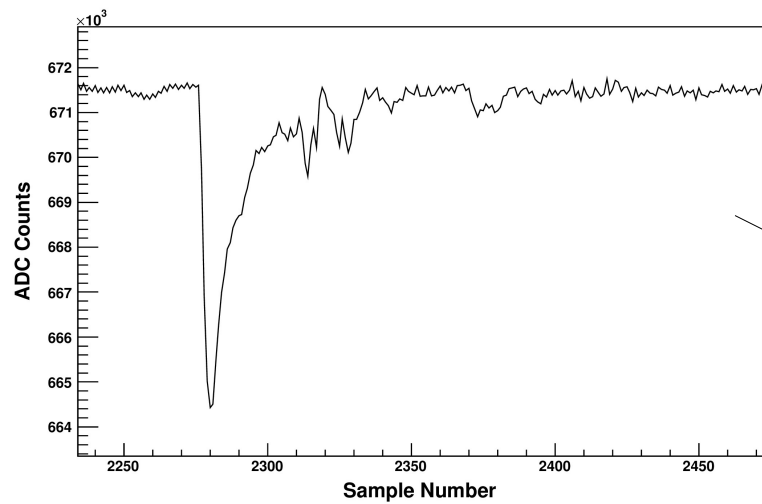
[3] NIST, ASTAR: stopping power and range tables for helium <http://physics.nist.gov/PhysRefData/Star/Text/ASTAR.html>.

The NEXT-DBDM prototype:

- Simulation: electron recoils in pure HPXe, $F = 0.15$, 10% optical efficiency: by Justo Martin-Albo, IFIC, Valencia



The NEXT-DBDM prototype:



A typical event

Neutron vs. electron recoils:

Studies in liquid Xe; gas Xe should be similar

- S2/S1 nuclear recoil discrimination
- use neutrons to produce nuclear recoils for calibration

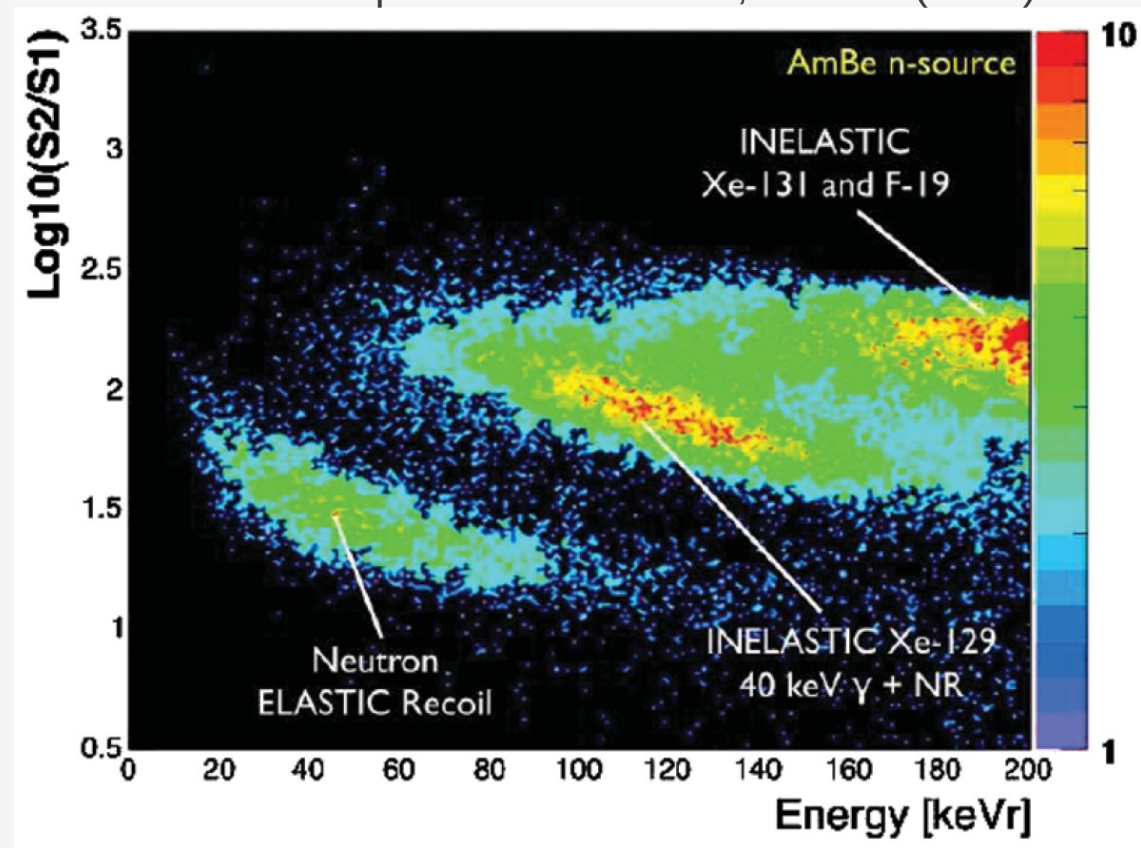
Example: XENON prototype [1]

5 Ci Am/Be neutron source

- 5 pe/keVee (1 pe/keVr) S1
- 8.4 pe/electron S2
- $> \sim 7.5\%$ light collection efficiency

We attempt similar measurements in ~ 14 bar gaseous xenon

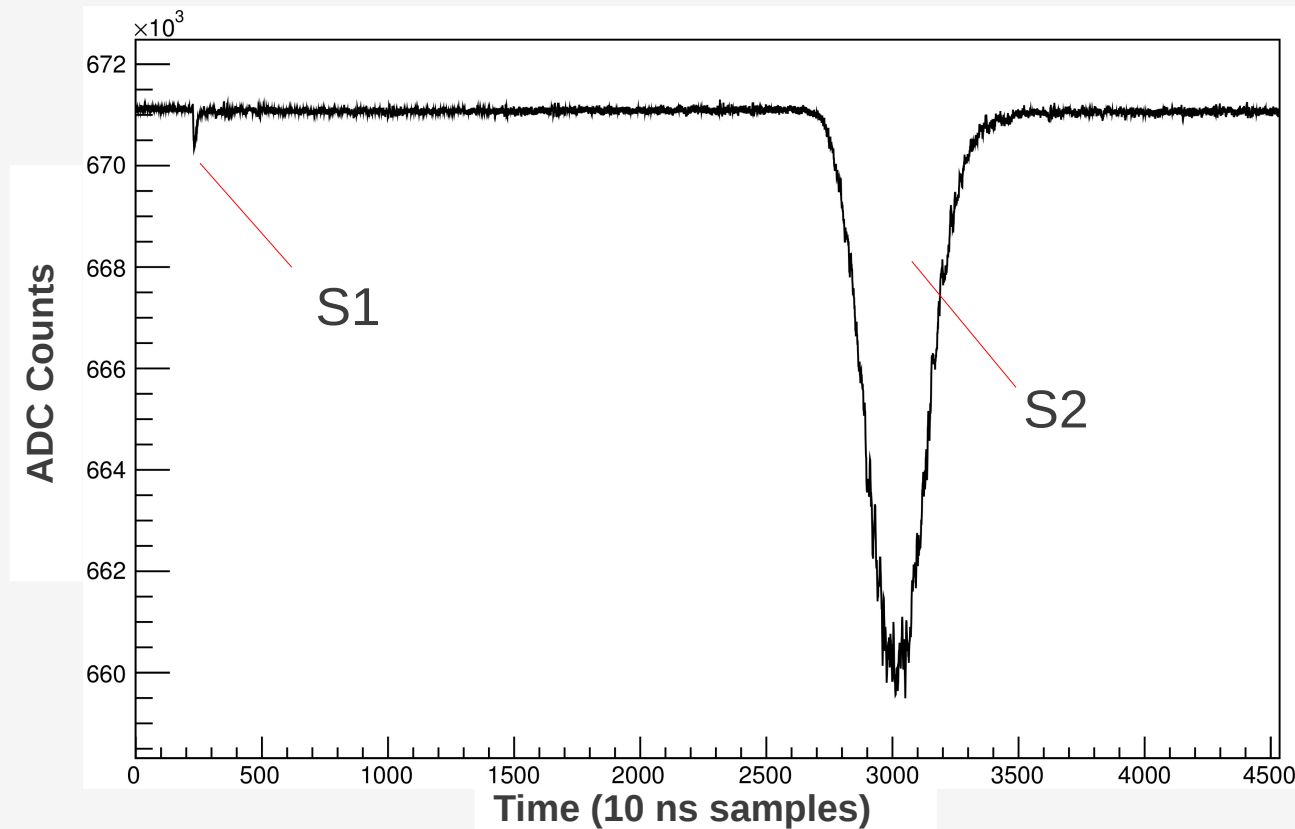
From: E. Aprile *et. al.* PRL 97, 081302 (2006)



Preliminary detection of nuclear recoils:

Example of a candidate neutron event:

- nuclear recoil produces a short track
- single, Gaussian-shaped pulse



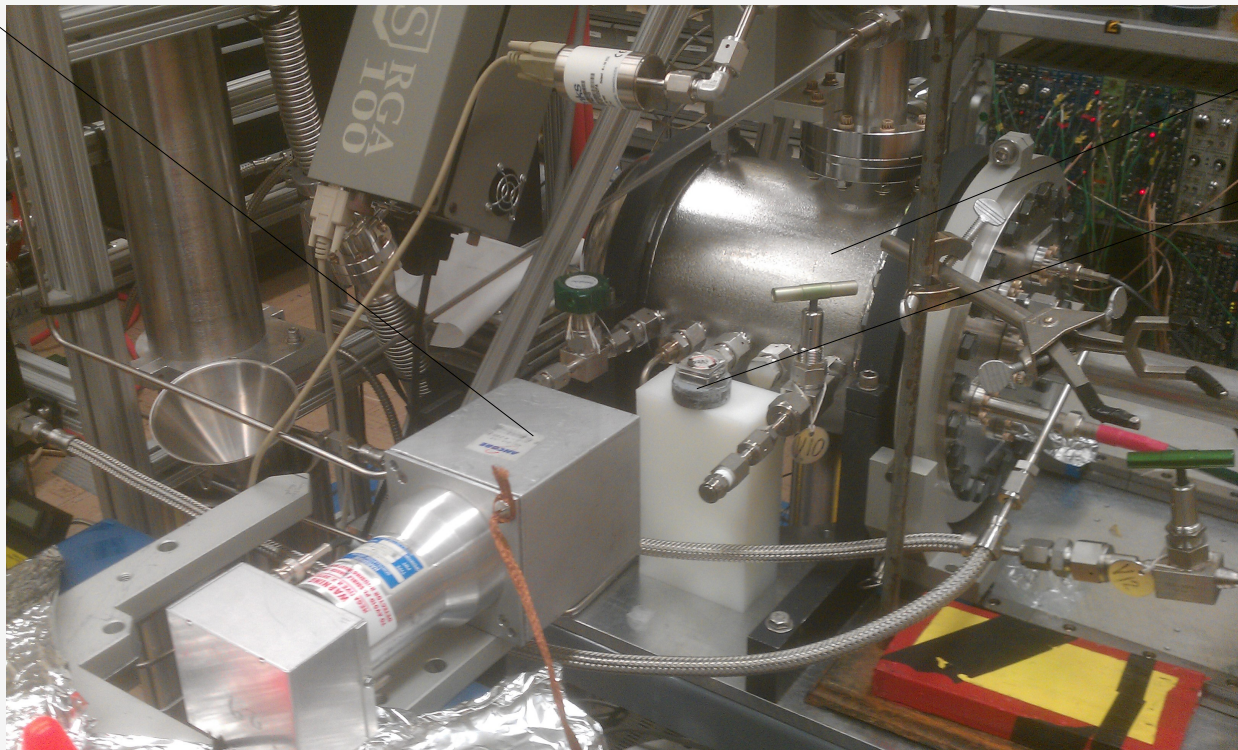
* Thanks to Yasuhiro Nakajima for reducing our electronic noise significantly

Preliminary detection of nuclear recoils:

Electron-positron annihilation radiation

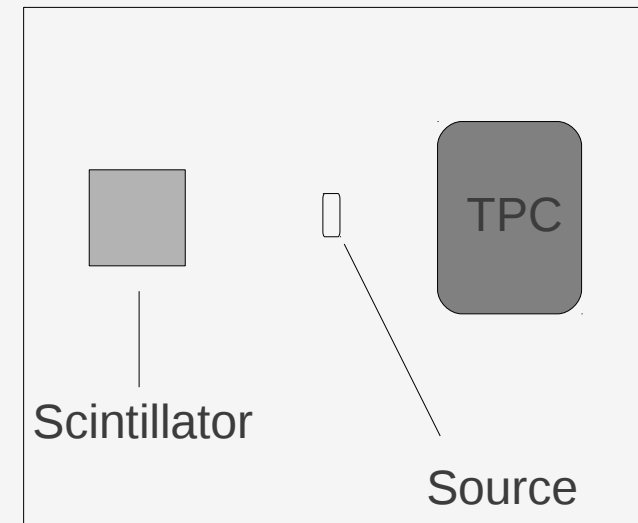
- Coincidence between collinear 511 keV gamma rays
- Same trigger conditions as neutron run (except NaI scintillator region of interest)

NaI scintillator



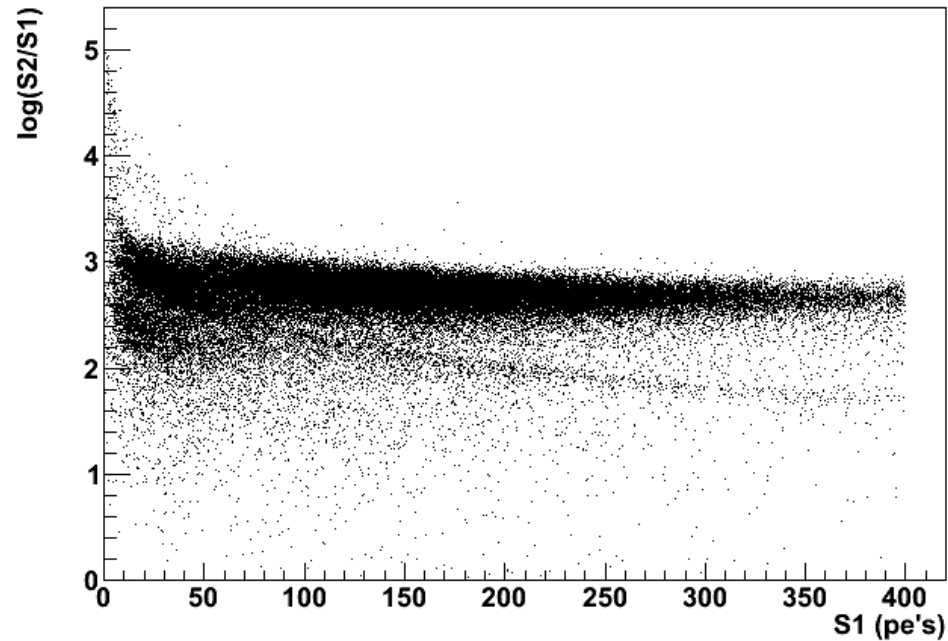
TPC

^{22}Na source

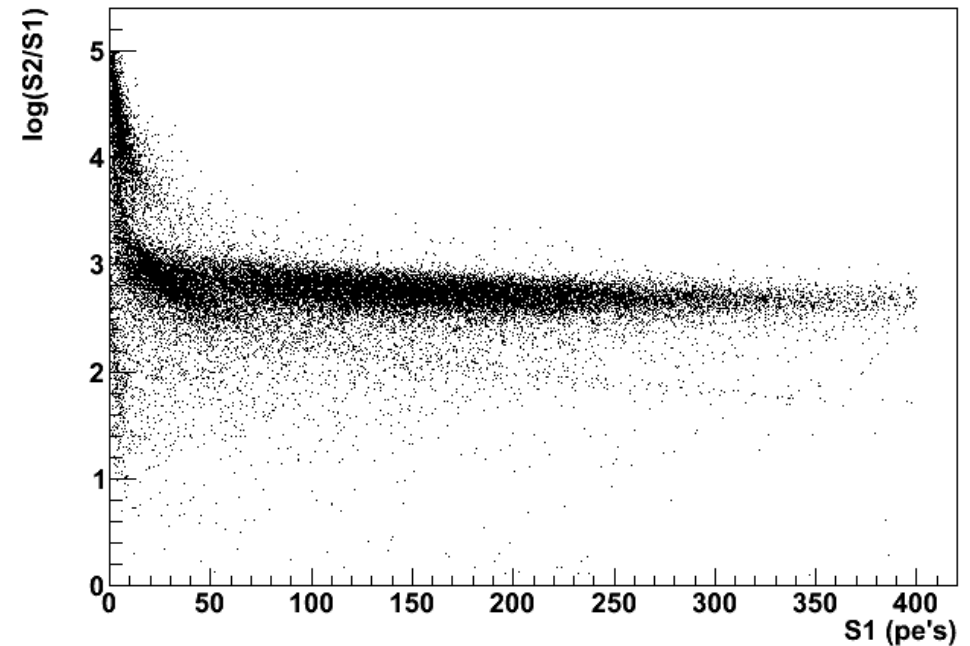


Preliminary detection of nuclear recoils:

S2/S1 recoil identification: γ vs. neutron sources

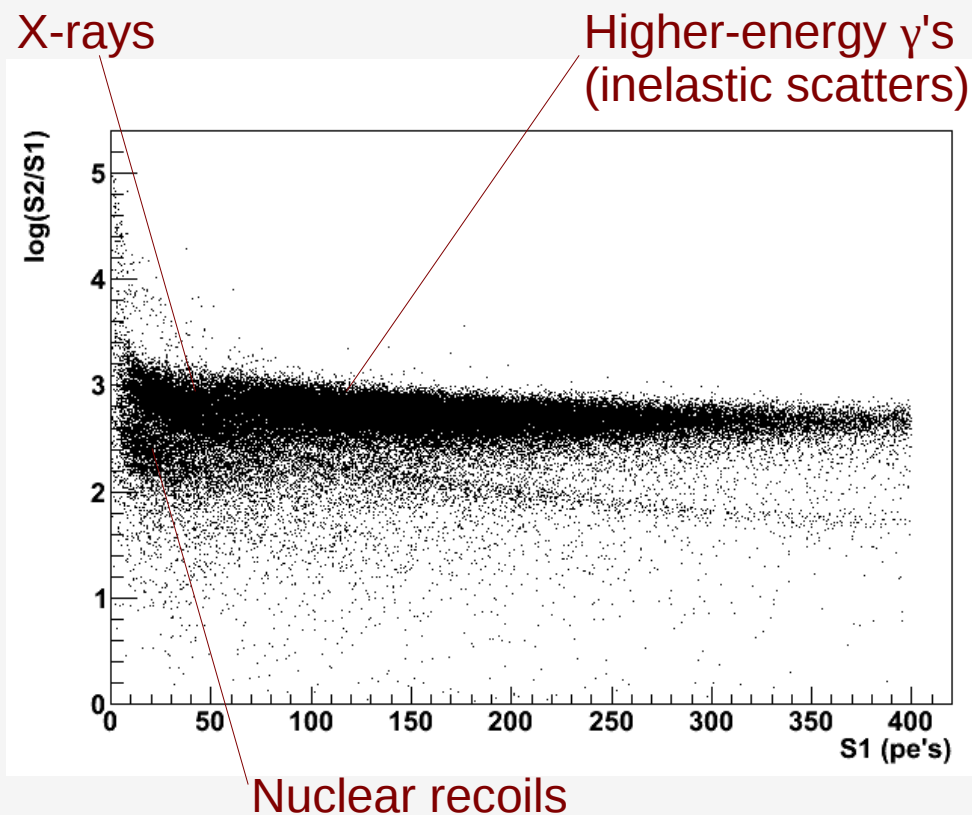


Neutron source

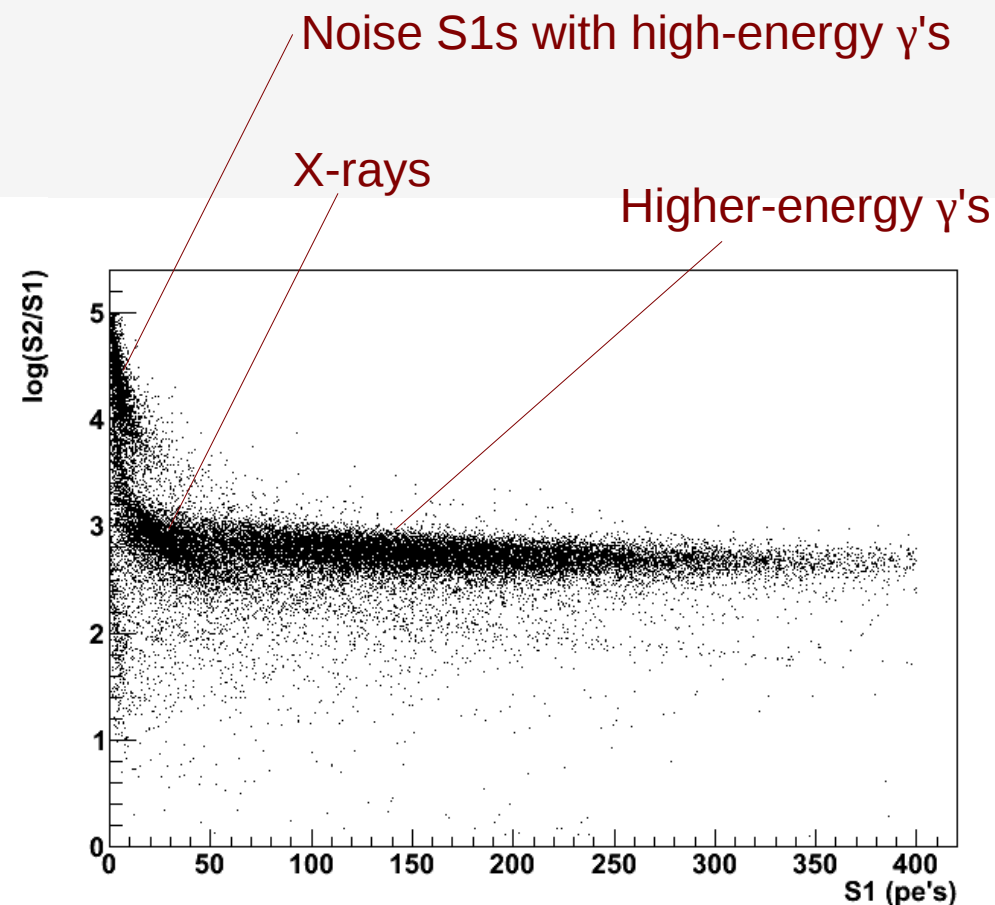


Gamma source

Preliminary detection of nuclear recoils:



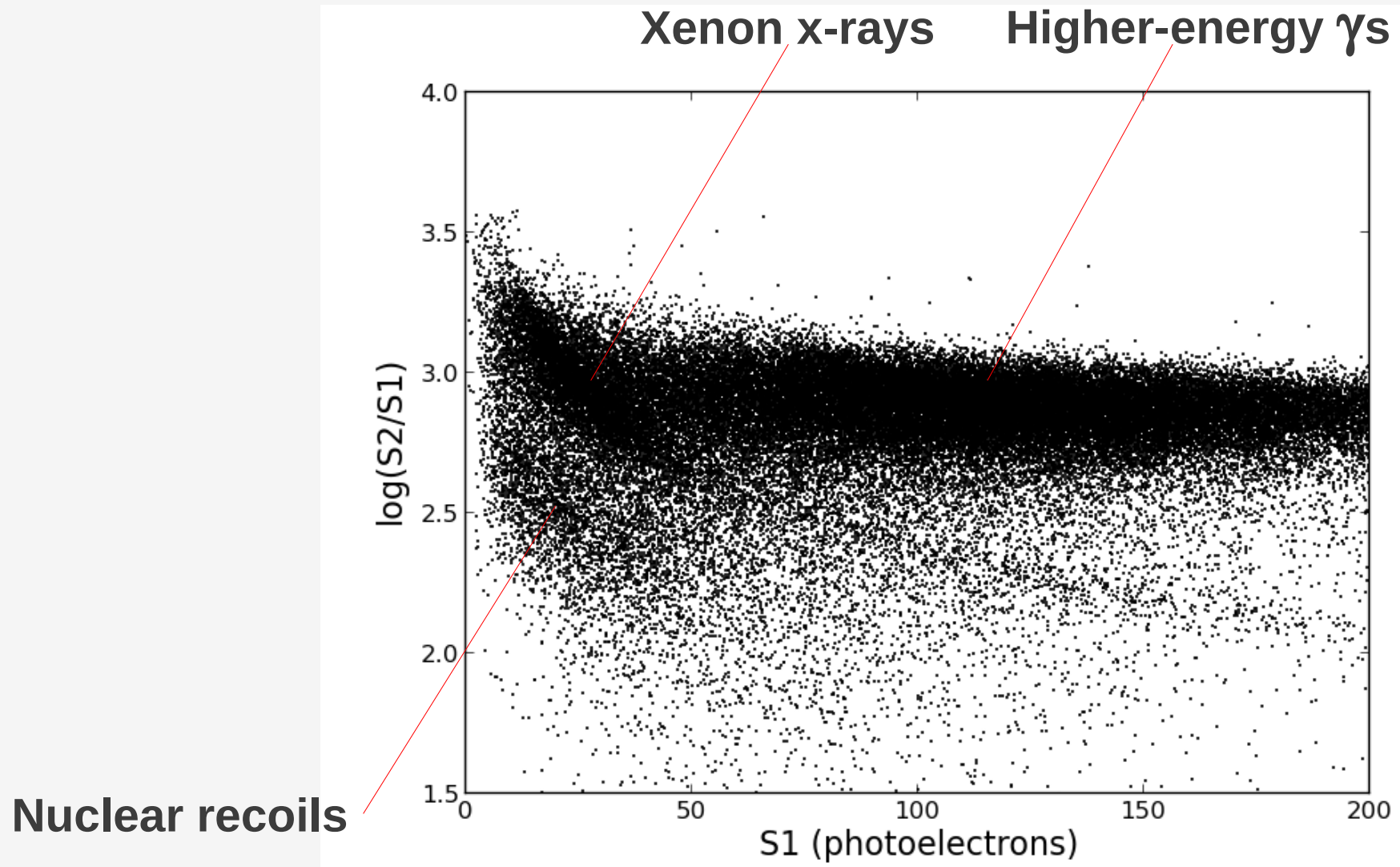
Neutron source



Gamma source

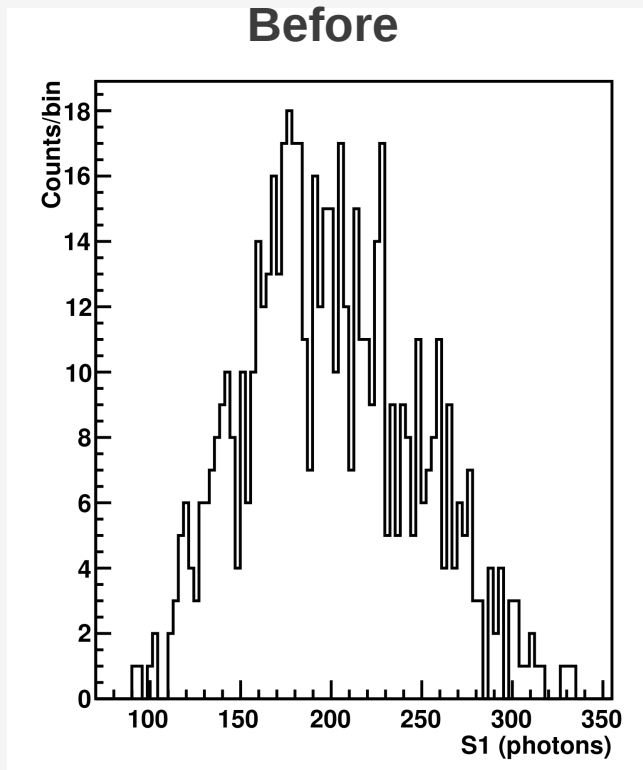
Preliminary detection of nuclear recoils:

S2/S1 recoil identification (~ 14 bar gaseous Xe)

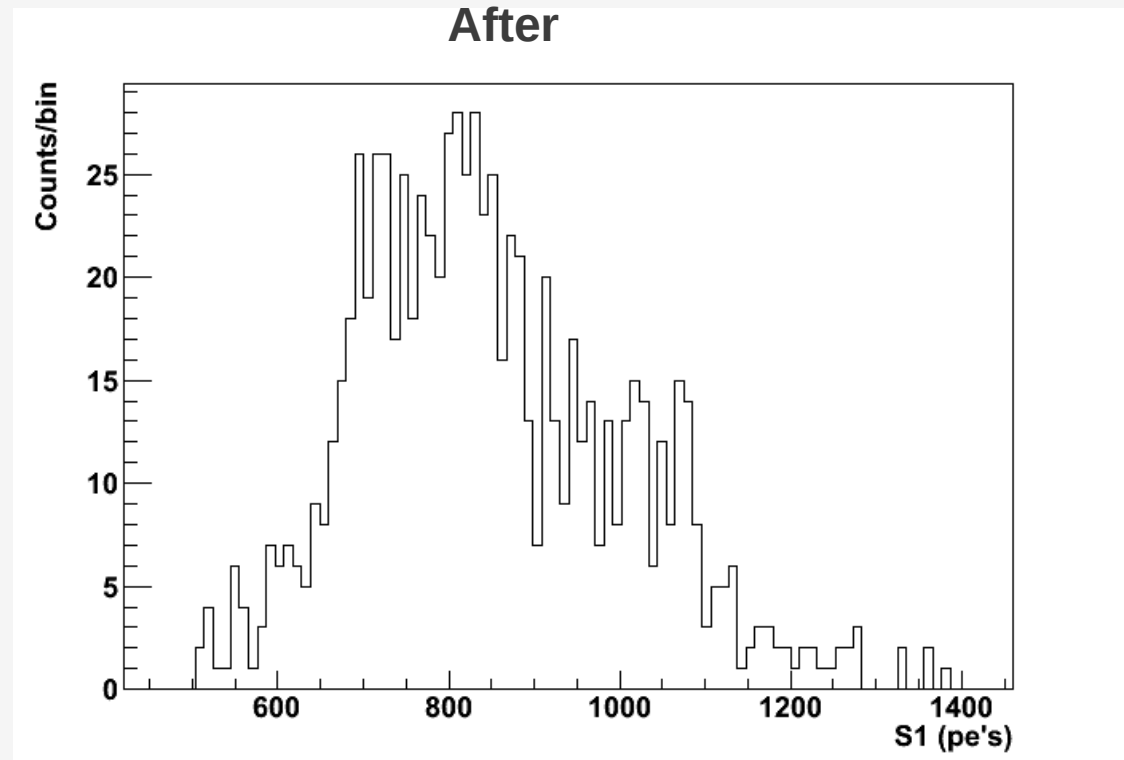


Preliminary detection of nuclear recoils:

- How TPB helped



~ 511 keV gammas;
~ 200 average S1 photons
~ **0.4 photons/keV**



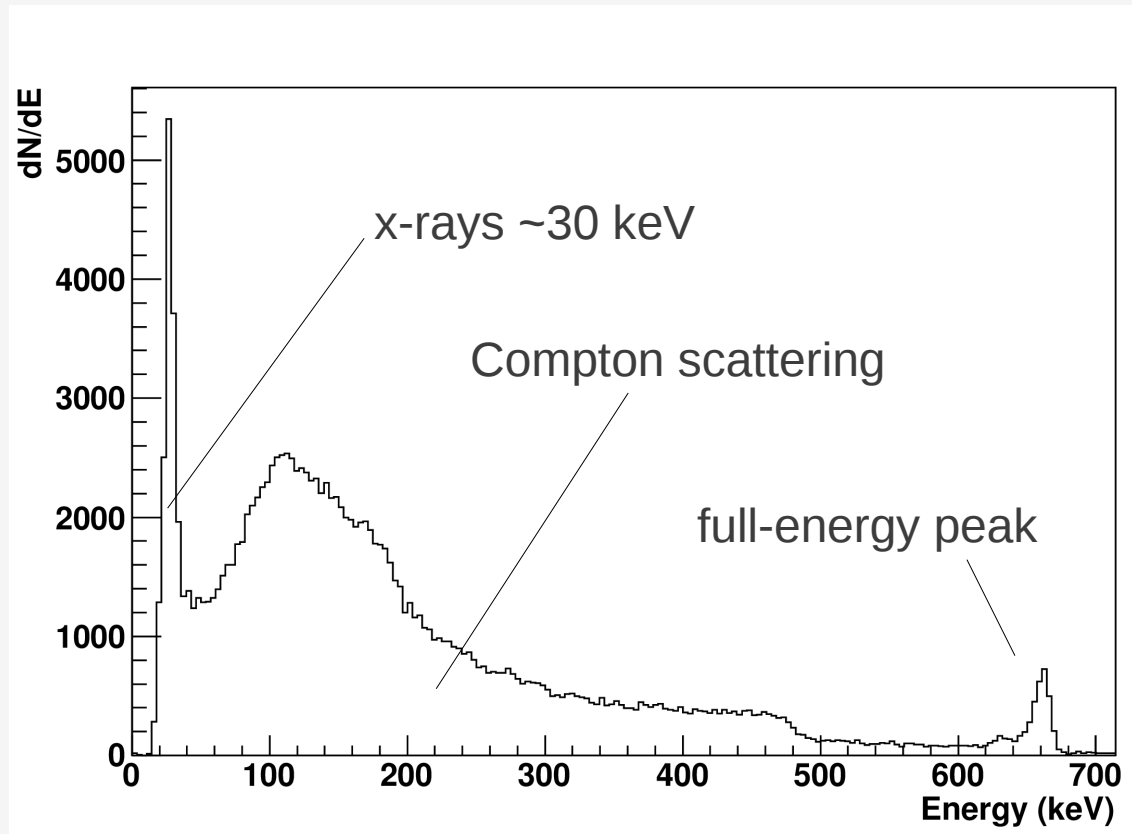
~ 662 keV gammas;
~ 800 average S1 photons
~ **1.2 photons/keV**

*** Approx. factor of 3 improvement in light yield**
(Note: drift fields were not matched)

Preliminary detection of nuclear recoils:

Energy spectrum for ^{137}Cs source:

- Peaks integrated and identified as S1 or S2
- S2 proportional to energy of event
- No corrections on physics applied



Preliminary detection of nuclear recoils:

Position-dependence

- Events located radially outward from central point register lower in E
- Correct with radial cut (r^*) for now
- Better tracking will improve correction capabilities

